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Self-Excited Induction Generators

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4.1 Introduction

By self-excited induction generators (SEIGs), we mean cage rotor induction machines with shunt (and series) capacitors connected at their terminals for self-excitation.

The shunt capacitors may be constant or may be varied through power electronics (or step-wise). SEIGs may be built with single-phase or three-phase output and may supply alternating current (AC) loads or AC rectified (direct current [DC]) autonomous loads. We also include here SEIGs connected to the power grid through soft-starters or resistors and having capacitors at their terminals for power factor compensation (or voltage stabilization).

Note that power electronics controlled cage rotor induction generators (IGs) for constant voltage and frequency output at variable speed, for autonomous and power grid operation, will be treated in [Chapter 5](#).

This chapter will introduce the main schemes for SEIGs and their steady-state and transient performance, with sample results for applications such as wind machines, small hydrogenerators, or generator

sets. Both power grid and stand-alone operation and three-phase and single-phase output SEIGs are treated in this chapter.

4.2 The Cage Rotor Induction Machine Principle

The cage rotor induction machine is the most built and most used electric machine, mainly as a motor, but, recently, as a generator, too.

The cage rotor induction machine contains cylindrical stator and rotor cores with uniform slots separated by a small airgap (0.3 to 2 mm in general).

The stator slots host a three-phase or a two-phase AC winding meant to produce a traveling magnetomotive force (mmf). The windings are similar to those described for synchronous generators (SGs) in Chapter 4 of *Synchronous Generators* or for wound rotor induction generators (WRIGs) in [Chapter 3](#) of this book. This traveling mmf produces a traveling flux density in the airgap, B_{g10} :

$$B_{g10} = \frac{\mu_0 F_{10}}{g} \cos(\omega_1 t - p_1 \theta_r) \quad (4.1)$$

g – airgap

$$F_{10} = \frac{3\sqrt{2} I_{10} W_1 K_{w1}}{\pi p_1} \quad (\text{for three phases}) \quad (4.2)$$

where

θ_r is the rotor position

p_1 equals the pole pairs

The cage rotor contains aluminum (or copper, or brass) bars in slots. They are short-circuited by end-rings with resistances that are smaller than those of bars (Figure 4.1).

The angular speed of the traveling fields is obtained for the following:

$$\omega_1 t - p_1 \theta_r = \text{const.} \quad (4.3)$$

That is, for

$$\frac{d\theta_r}{dt} = \frac{\omega_1}{p_1}; \quad n_1 = \frac{f_1}{p_1} \quad (4.4)$$

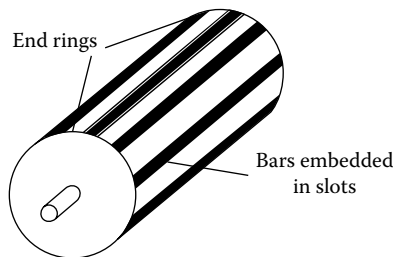


FIGURE 4.1 The cage rotor.

The speed n_1 (in revolutions per second r/sec) is the so-called ideal no-load or synchronous speed and is proportional to stator frequency and inversely proportional to the number of pole pairs p_1 .

The traveling field in the airgap induces electromagnetic fields (emfs) in the rotor that rotate at speed n , at frequency f_2 :

$$f_2 = \left(\frac{n_1 - n}{n_1} \right) \cdot f_1 = S f_1$$

$$S = \frac{n_1 - n}{n_1}$$
(4.5)

As expected, the emfs induced in the short-circuited rotor bars produce in them AC currents at slip frequency $f_2 = S f_1$.

Let us now assume that the symmetric rotor cage, which has the property to adapt to almost any number of pole pairs in the stator, may be replaced by an equivalent (fictitious) three-phase symmetric three-phase winding (as in WRIGs) that is short-circuited. The traveling airgap field produces symmetric emfs in the fictitious three-phase rotor with frequency that is $S f_1$ and with amplitude that is also proportional to slip S :

$$E_2 = S E_1 = S \omega_1 L_m I_m$$
(4.6)

where L_m is the magnetization inductance.

E_1 is the stator phase self-induced emf, generally produced by both stator and rotor currents, or by the so-called magnetization current I_m ($I_m = I_1 + I_2$).

The rotor phases may be represented by a leakage inductance L_{2l} and a resistance R_2 . Consequently, the rotor current I_2 is as follows:

$$I_2 = \frac{S E_1}{\sqrt{(R_2)^2 + (S \omega_1 L_{2l})^2}}$$
(4.7)

The rotor currents interact with the airgap field to produce tangential forces — torque. In Equation 4.6 and Equation 4.7, the rotor winding is reduced to the stator winding based on energy (and loss) equivalence.

Noticing that the stator phases are also characterized by a resistance R_1 and a leakage inductance L_{1l} , the stator and rotor equations may be written, for steady state, in complex numbers, as for a transformer but with different frequencies in the primary and secondary. Let us consider the generator association of signs for the stator:

$$\begin{aligned} \underline{I}_1 (R_1 + j \omega_1 L_{1l}) + \underline{V}_1 &= \underline{E}_1 \\ \underline{I}_r (R_2 + j S \omega_1 L_{2l}) &= S \underline{E}_1 \\ \underline{E}_1 &= -j \omega_1 L_m (\underline{I}_s + \underline{I}_r) \end{aligned}$$
(4.8)

Dividing the second expression in Equation 4.8 by S yields the following:

$$\underline{I}_2 \left(R_2 + \frac{R_2 (1-S)}{S} + j \omega_1 L_{2l} \right) = \underline{E}_1$$
(4.9)

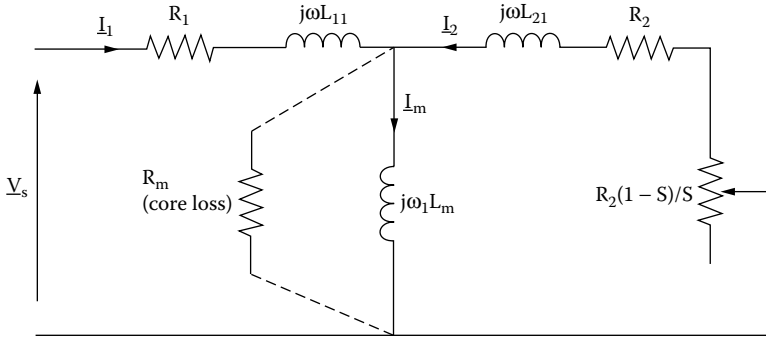


FIGURE 4.2 The cage rotor induction machine equivalent circuit.

This way, in fact, the frequency of rotor variables becomes ω_r , and it refers to a machine at standstill, but with an additional (fictitious) rotor resistance $R_2(1 - S)/S$. The power dissipated in this resistance equals the mechanical power in the real machine (minus the mechanical losses):

$$T_e \cdot 2\pi n_1(1 - S) = 3I_2^2 R_2 \frac{(1 - S)}{S} \quad (4.10)$$

Finally,

$$T_e = \frac{3p_1}{\omega_1} I_2^2 \frac{R_2}{S} = 3 \frac{p_1}{\omega_1} P_{elm} \quad (4.11)$$

P_{elm} is the so-called electromagnetic power: the total active power that crosses the airgap. Equation 4.8 and Equation 4.9 lead to the standard equivalent circuit of the induction machine (IM) with cage rotor (Figure 4.2).

The core loss resistance R_m is added to account for fundamental core losses located in the stator, as $S \ll 1$, in general. R_m is determined by tests or calculated in the design stage. As can be seen from Equation 4.11, the electromagnetic power P_{elm} is positive (motoring) for $S > 0$ and negative (generating) for $S < 0$. For details on parameter expressions, various losses, parasitic torques, design, and so forth, of cage rotor IMs, see Reference [1].

As seen from Figure 4.2, the equivalent (total) reactance of the IM is always inductive, irrespective of slip sign (motor or generator), while the equivalent resistance changes sign for generating. So, the IM takes the reactive power to get magnetized either from the power grid to which it is connected or from a fixed (or controlled) capacitor at terminals. Note that when a full power static converter is placed between the IG and the load (or power grid), the IG is again self-excited by the capacitors in the converter's DC link or from the power grid (if a direct AC–AC converter is used).

As the operation of an IM at the power grid is straightforward ($S < 0$, $\omega_r > \omega_1$) the capacitor-excited induction generator will be treated here first in detail.

4.3 Self-Excitation: A Qualitative View

The IG with capacitor excitation is driven by a prime mover with the main power switch open (Figure 4.3a). As the speed increases, due to prime-mover torque, eventually, the no-load terminal voltage increases and settles to a certain value, depending on machine speed, capacitance, and machine parameters.

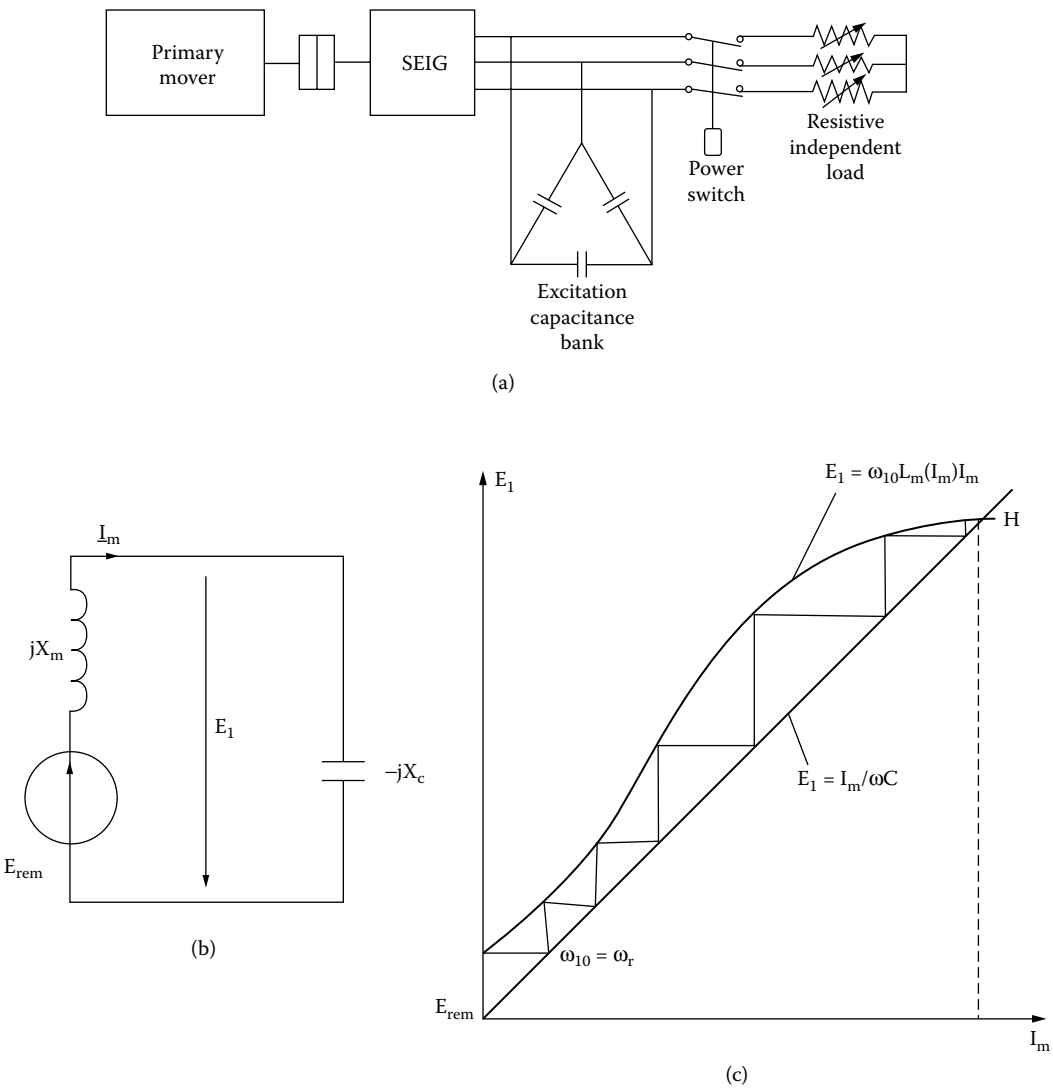


FIGURE 4.3 Self-excitation on self-excited induction generator (SEIG): (a) the general scheme, (b) oversimplified equivalent circuit, and (c) quasi-steady-state self-excitation characteristics.

The equivalent circuit (Figure 4.2) is further simplified by neglecting the stator resistance and leakage inductance and by considering zero slip ($S = 0$: open rotor circuit) for no-load conditions (Figure 4.3b). E_{rem} represents the no-load initial stator voltage (before self-excitation), at frequency $\omega_{10} = \omega_r$, produced by the remnant flux density in the rotor left there from previous operation events.

To initiate the self-excitation process, E_{rem} has to be nonzero. The magnetization curve of the IG, obtained from typical motor no-load tests, $E_1(I_m)$, has to advance to the nonlinear (saturation) zone in order to firmly intersect the capacitor straight-line voltage characteristic (Figure 4.3c) and, thus, produce the no-load voltage E_1 . The process of self-excitation of IG has been known for a long time [2].

The increasing of the terminal voltage from V_{rem} to V_{10} unfolds slowly in time (seconds), and Figure 4.3c presents it as a step-wise quasi-steady-state process. It is a qualitative representation only. Once the SEIG

is self-excited, the load is connected. If the load is purely resistive, the terminal voltage decreases and so does (slightly) the frequency ω_1 for constant (regulated) prime-mover speed ω_r .

With $\omega_1 < \omega_r$, the SEIG delivers power to the load for negative slip $S < 0$:

$$f_1 = \frac{np_1}{1+|S|}; \quad S < 0 \quad (4.12)$$

The computation of terminal voltage V_1 , frequency f_1 , stator current I_1 , delivered active and reactive power (efficiency) for given load (speed n), capacitor C , and machine parameters $R_1, R_2, L_{1b}, L_{2b}, L_m(I_m)$ represents, in fact, the process of obtaining the steady-state performance.

The nonlinear function $L_m(I_m)$ — magnetization curve — and the variation of frequency f_1 with load, at constant speed n , make the process mathematically intricate.

4.4 Steady-State Performance of Three-Phase SEIGs

Various analytical (and numerical) methods to calculate the steady-state performance of SEIGs were proposed. They seem, however, to fall into two main categories:

- Loop impedance models [3]
- Nodal admittance models [4]

Both models are based on the SEIG equivalent circuit (Figure 4.2) expressed in per unit (P.U.) form for frequency f (P.U.) and speed U (in P.U.) as follows:

$$\begin{aligned} f &= f_1/f_{1b}; \\ U &= np_1/f_{1b} \end{aligned} \quad (4.13)$$

The base frequency for which all reactances $X_{1b}, X_{2b}, X_m(I_m)$ are calculated is f_{1b} .

With an R_L, L_L, C_L load, the equivalent circuit in Figure 4.2 with speed and frequency in P.U. terms becomes as shown in Figure 4.4.

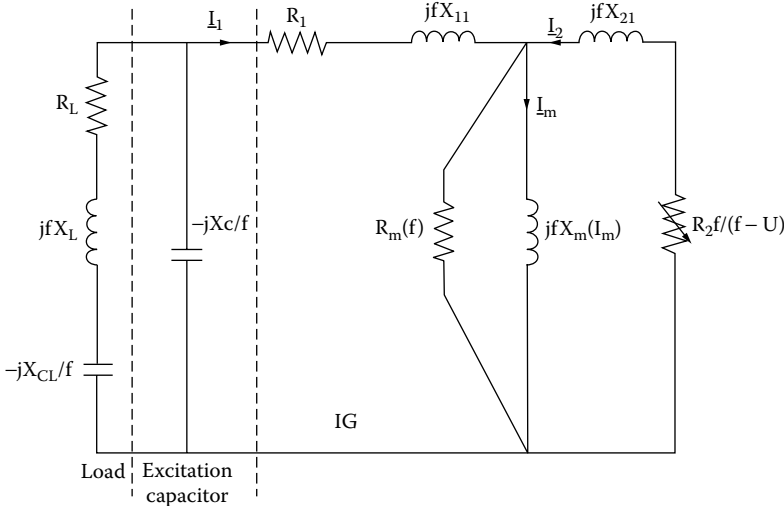


FIGURE 4.4 Self-excited induction generator (SEIG) equivalent circuit in per unit (P.U.) frequency f and speed U .

In general, both R_{1L} and X_{1L} are dependent on frequency f (P.U.), though they get simplified forms if only a resistive or an R_L , X_L (an induction motor) is considered.

For self-excitation, the summation of currents in the node should be zero (with $E_1 \neq 0$):

$$-I_1 + I_m - I_2 = 0 \quad (4.16)$$

or

$$f \underline{E}_1 \cdot \left(\frac{1}{R_{1L} + jfX_{1L}} + \frac{S}{R_2 + jfSX_{2l}} + \frac{1}{jfX_m} \right) = 0 \quad (4.17)$$

The real and imaginary parts in Equation 4.17 have to be zero for self-excitation (it is, in fact, an energy balance condition):

$$\frac{R_{1L}}{R_{1L}^2 + f^2 X_{1L}^2} + \frac{SR_2}{R_2^2 + S^2 f^2 X_{2l}^2} = 0 \quad (4.18)$$

$$\frac{1}{fX_m} - \frac{fX_{1L}}{R_{1L}^2 + f^2 X_{1L}^2} + \frac{SfX_{2l}}{R_2^2 + S^2 f^2 X_{2l}^2} = 0 \quad (4.19)$$

For given frequency f (P.U.), Equation 4.18 remains (for given excitation capacitors, IG parameters, and load), with only one unknown, the slip S :

$$aS^2 + bS + c = 0 \quad (4.20a)$$

with

$$\begin{aligned} a &= f^2 X_{2l}^2 R_{1L}, \\ b &= R_2 \left(R_{1L}^2 + f^2 X_{1L}^2 \right) \\ c &= R_{1L} R_2^2 \end{aligned} \quad (4.20b)$$

Equation 4.20 has two solutions, but only the smaller one (in amplitude) is really useful. For the larger one, most of the power is consumed into the rotor resistance:

$$S_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (4.21)$$

If complex solutions of S are obtained, it means that self-excitation is impossible.

With slip S_1 found from Equation 4.21, for given f , the corresponding P.U. speed $U = f - S$ is determined. With $S = S_1$, from Equation 4.19, the magnetization reactance X_m is calculated as follows:

$$X_m = f^{-1} \left[\frac{fX_{1L}}{R_{1L}^2 + f^2 X_{1L}^2} - \frac{SfX_{2L}}{R_2^2 + S^2 f^2 X_{2L}^2} \right]^{-1} < X_{max} \quad (4.22)$$

X_{max} is the maximum (unsaturated) value of the magnetization reactance (at base frequency f_{1b}). With $X_m > X_{max}$, self-excitation is again impossible.

Further on, from no-load motor testing, or from design calculations, the $E_1(I_m)$ or $X_m(I_m) = E_1/I_m$ characteristic will be determined (Figure 4.6).

$E_1(X_m)$ from Figure 4.6 may be curve fitted by mathematical approximations such as the following [11]:

$$E_1 = \omega_{1b} K_1 I_m; \quad I_m < I_0$$

$$E_1 = \omega_{1b} \left[K_1 I_m + \frac{K_2}{d} \tan^{-1}(d(I_m - I_0)) \right] \quad (4.23)$$

for $I_m \geq I_0$.

The coefficients K_1, K_2, d are calculated to preserve continuity at $I_m = I_0$ in E_1 and in dE_1/dI_m , and they reasonably approximate the entire curve. This particular approximation has a steady decrease in the derivative, and its inverse is readily available:

$$X_m = X_{max} = K_1 \omega_{1b} \quad \text{for } I_m < I_0 \quad (4.24)$$

$$E_1 = X_m \left[I_0 + \frac{1}{d} \tan \left(\frac{E_1(1 - X_{max}/X_m)}{dK_2 \omega_{1b}} \right) \right]; \quad I_m > I_0 \quad (4.25)$$

Though Equation 4.25 is a transcendental equation, its numerical solution in E_1 , for the now calculated X_m (Equation 4.22), is rather straightforward.

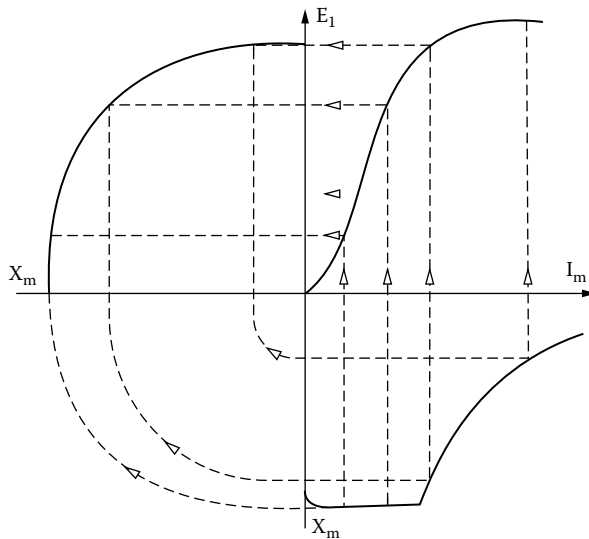


FIGURE 4.6 Magnetization curve at base frequency f_{1b} .

Once E_1 is known, the equivalent circuit in Figure 4.5 produces all required variables:

$$\begin{aligned}
 I_2 &= \frac{-fE_1}{\frac{R_2}{s} + jfX_{2l}}; \quad I_m = \frac{E_1}{jX_m} \\
 I_1 &= \frac{-fE_1}{R_{1l} + jfX_{1l}}; \quad X_{1l} < 0; \\
 -V_1 &= fE_1 + (R_1 + jfX_{1l})I_1 \\
 I_c &= -V_1 j \frac{1}{fX_c}; \quad X_c = \frac{1}{\omega_1 C} \\
 I_L &= I_1 + I_c \\
 I_m &= I_1 + I_2
 \end{aligned} \tag{4.26}$$

Let us now draw a general phasor diagram for a typical R_L, L_L load when the load current I_L is lagging behind the terminal voltage V_1 . Also, notice in Equation 4.26 that I_1 is leading fE_1 , because $V_{1l} < 0$ to fulfill the self-excitation conditions.

The phasor diagram starts with fE_1 in the real axis and I_1 leading it (Figure 4.7). Then, from Equation 4.26 (the third expression), V_1 is constructed. Also, from Equation 4.26 (the first expression), for $S < 0$, I_2 is ahead of I_1 . For resistive-inductive load, the capacitor current is in a leading position with respect to terminal voltage.

The whole computation process described so far may be computerized, and, for given speed U (P.U.), the initial value of f may be taken as $f(1) = U$. After one computation cycle, the slip $S(1)$ is calculated, and the new value $f(2)$ is $f(2) = v + S(1)$. The whole iterative process continues until the frequency error between two successive computation cycles is smaller than a desired value.

It was demonstrated [9] that less than ten cycles are required, even if the core loss resistance (R_m) would be included. It was also shown that core losses do not modify the machine capability, except for the situation around maximum power delivery.

Once fE_1 is known, power core losses p_{iron} may be calculated as follows:

$$p_{iron} \approx \frac{3(fE_1)^2}{R_m} \tag{4.27}$$

So, the efficiency on SEIG is

$$\eta = \frac{3V_1 I_L \cos \phi_L}{3V_1 I_L \cos \phi_L + 3R_1 I_1^2 + 3R_2 I_2^2 + p_{iron} + p_{mec} + p_{stray} + p_{cap}} \tag{4.28}$$

In Equation 4.28, p_{mec} is the mechanical loss, p_{stray} is the IG stray load loss (Reference [1], Chapter 3), and p_{cap} is the excitation capacitor loss.

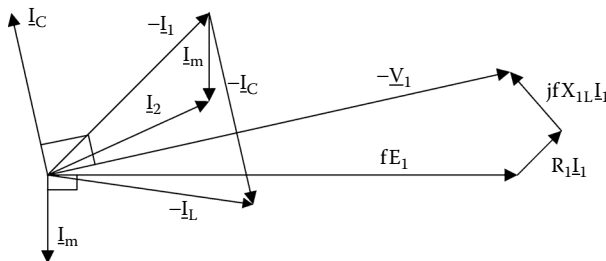


FIGURE 4.7 The phasor diagram.

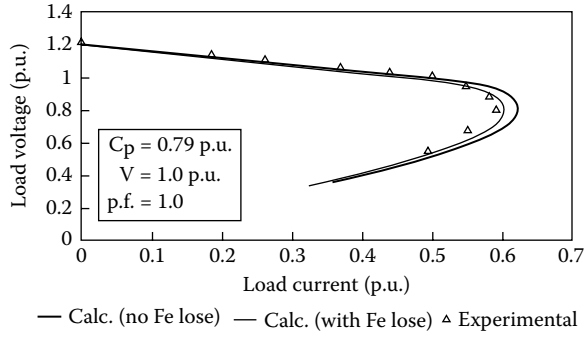


FIGURE 4.8 Voltage vs. load current of self-excited induction generator (SEIG) with shunt self-excitation.

Typical load voltage V_L vs. load current I_L for unity power factor load ($\phi_L = 0$), for a 20 kW, four-pole, 50 Hz, 380 V (Y), 5.4 A star connected machine are shown in Figure 4.8 [9]. The machine parameters are $R_1 = 0.10$ P.U., $X_{1l} = 0.112$ P.U., $R_2 = 0.0736$ P.U., $X_{2l} = 0.1$ P.U., and

$$\begin{aligned}
 E_1(P.U.) &= 1.345 - 0.203X_m; & X_m < 1.728 P.U. \\
 E_1(P.U.) &= 1.901 - 0.525X_m; & 1.728 \leq X_m \leq 2.259 \\
 E_1(P.U.) &= 3.156 - 1.08X_m; & 2.259 \leq X_m \leq 2.446 \\
 E_1(P.U.) &= 37.79 - 15.12X_m; & 2.446 \leq X_m \leq 2.48. \\
 0; & X_m > 2.48
 \end{aligned} \tag{4.29}$$

$$R_m = 18.51 + E_1 \times 4.197$$

The typical collapse of terminal voltage, even at resistive load ($\phi_L = 0$), below rated machine current, is evident.

4.4.2 SEIGs with Series Capacitance Compensation

In an attempt to increase the load range (in P.U.), series capacitors are added in short shunt (Figure 4.9a) or long shunt (Figure 4.9b) connections.

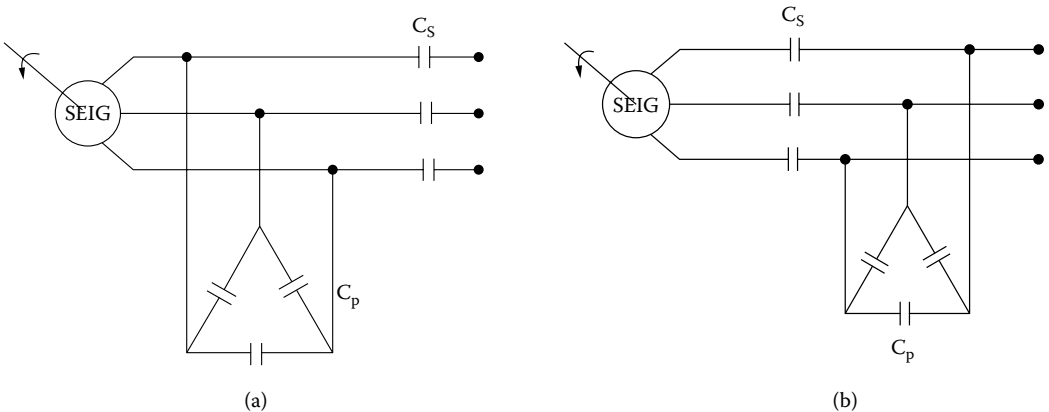


FIGURE 4.9 Series compensation by capacitance: (a) short shunt and (b) long shunt.

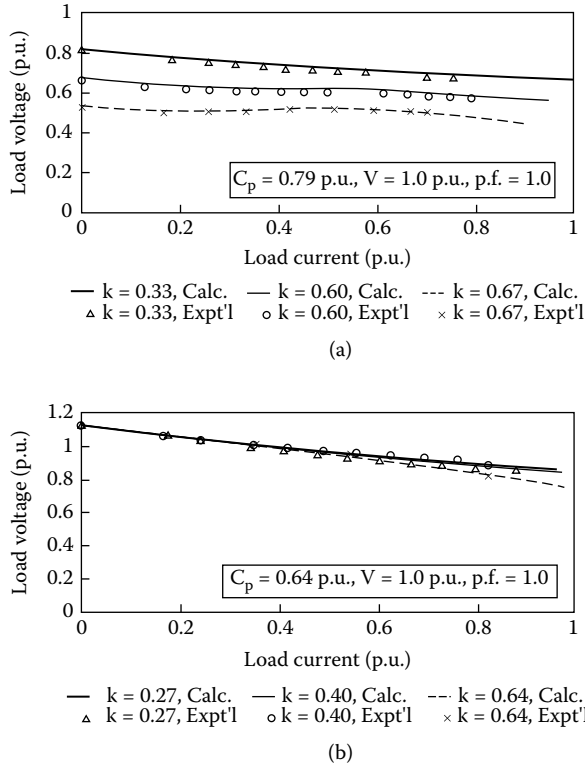


FIGURE 4.10 Load curve of three phase SEIG with series compensation: (a) long shunt, (b) short shunt.

The short shunt was proven superior in extending the stable operation load range for the same capacitance effort. The investigation of both connections can be done by following the iterative method in the previous paragraph by incorporating $(-jX_{cs}/f)$ in the load (short shunt) or to the stator leakage reactance fX_{ll} (long shunt). Typical load voltage/current curves with long shunt and short shunt compensation, for the same machine, are shown in Figure 4.10 [9], with $K = X_{cs}/X_{cp}$ as the ratio between series and parallel capacitor reactances (Figure 4.10a and Figure 4.10b).

Though the voltage collapse was avoided up to rated machine current, the voltage regulation is still noticeable for both connections. Notice that the parallel capacitor C_p is larger for the long shunt connection ($K = C_s/C_p$).

4.5 Performance Sensitivity Analysis

In this analysis, the influence of IG resistances R_1, R_2 , leakage reactances X_{1l}, X_{2l} , magnetization reactance X_m , and parallel and series capacitances C_p, C_s on a SEIG's performance is investigated for constant speed (controlled prime mover) and constant head hydroturbine or uncontrolled speed wind turbine.

4.5.1 For Constant Speed

- The no-load voltage increases with the parallel (excitation) capacitance C_p .
- The maximum output power and terminal voltage increase significantly with capacitance C_p .
- For constant load voltage, the required capacitor C_p increases with delivered power.
- When no-load voltage increases, the magnetization reactance X_m decreases, due to advancing magnetic saturation.

- For self-excitation, a necessary but insufficient condition for purely resistive load R_L is (Equation 4.15) $X_{1L} < 0$:

$$fX_{1l} < X_L; \quad X_L = \frac{X_c/f}{1 + \frac{X_c^2}{f^2 R_L^2}} \quad (4.30)$$

With given capacitor (X_c), Equation 4.30 reduces itself to a minimum load resistance R_L condition:

$$R_L \geq X_c \sqrt{\frac{X_{1l}}{X_c - f^2 X_{1l}}} \quad (4.31)$$

The smaller the stator leakage reactance, the better (the smaller the value of R_L). Notice again that Equation 4.31 is a necessary but not sufficient condition.

- From Equation 4.21, a real value of S is required for self-excitation: $b^2 > 4ac$. For resistive load,

$$R_{1L}^2 + f^2 X_{1L}^2 > 2 \cdot R_{1L} \cdot f \cdot X_{2l} \quad (4.32)$$

or simply,

$$fX_{2l} < X_{1L} = -fX_{1l} + \frac{X_c/f}{1 + \frac{X_c^2}{f^2 R_L^2}} \quad (4.33)$$

Finally,

$$f(X_{1l} + X_{2l}) < \frac{X_c/f}{1 + \frac{X_c^2}{f^2 R_L^2}} \quad (4.34)$$

And,

$$R_L \geq X_c \sqrt{\frac{X_{1l} + X_{2l}}{X_c - (X_{1l} + X_{2l})f^2}} \quad (4.35)$$

- It is very clear that Equation 4.35 is stronger than Equation 4.31 and should be the only one of the two conditions to be considered for practical purposes.
- Smaller short-circuit reactance is better, while at least $X_c > (X_{1l} + X_{2l})f^2$. This corresponds to a large capacitor (perhaps the largest ideal limit).
- The largest slip S (Equation 4.21) is obtained for $b^2 = 4ac$, and for small slips, S_1 is

$$S_{1max} \approx \frac{-2ac}{2ab} \approx -\frac{c}{b} \quad (4.36)$$

For resistive load, S_1 becomes

$$S_{1max} \approx -\frac{R_2}{fX_{2l}} \quad (4.37)$$

Incidentally, this ideal condition (for S_{1max} the voltage already collapses) corresponds to maximum torque for constant airgap flux (E_1) control in vector controlled IMs.

4.5.2 For Unregulated Prime Movers

- Along a 40% load resistance variation — around maximum output power — the output power varies only a little.
- Within this rather constant power load range, however, the load voltage drops notably with load.
- Up to maximum power, the frequency and speed decrease with power, while they tend to increase after the maximum power load; a kind of self-stabilization, in this respect, takes place.
- The maximum power depends on $C_p^{2.2}$ and the corresponding load voltage, on $C_p^{0.5}$. This tends to be valid both for three-phase and single-phase SEIGs.
- For no load, the minimum capacitance for self-excitation is inversely proportional to speed squared.
- Under load, the minimum capacitance depends on speed, load impedance, and load power factor.
- When the capacitance is too small to handle the total reactive power (of IG and load) of the SEIG's voltage collapses. When the parallel capacitance C_p is too large, the rotor impedance of IG causes de-excitation, and the voltage collapses again. There should be an optimum capacitor between C_{pmin} and C_{pmax} to provide maximum output power for good efficiency.
- The linear (stable) zone of $V_1(I_L)$ curve can be extended notably — that is, larger maximum power with reasonable voltage regulation — by using a series capacitor $C_s(X_{cs})$. A good first guess for C_p corresponds to $X_{cp} \approx 0.7 - 0.8$ (P.U.) and $X_{cs} \approx 0.4 - 0.6 X_{cp}$ (see Reference [12] for more on capacitance selection). Again, there is an optimal series capacitor for a given SEIG to produce minimum average voltage regulation.
- Constant-speed-regulated prime movers lead to notably larger powers delivered by the SEIG for other given data.
- A combination of speed regulation and capacitance variation with load may provide rather constant voltage and frequency for up to rated load [13].
- Capacitance and speed coordinated control, in a simple rugged configuration, to provide voltage and frequency control, with a small droop for the entire power range, is still to be accomplished.

4.6 Pole Changing SEIGs for Variable Speed Operation

There are SEIG applications where the speed varies notably with the load, but a certain frequency and voltage regulation is allowed for. Such a case is wind power. As the wind turbine power varies with cubic speed, a 4/6 pole changing in the stator winding leads to a (4/6) speed variation and, thus, a reduction in power of $(4/6)^3 = 8/27$. This kind of reduction is practically acceptable. Either two windings with different ratings and pole numbers are inserted in the stator slots or a single winding is connected two ways for the two pole pairs: $p_1 < p'_1$ [14,15]. Provided the winding factors K_{w1} and K'_{w1} are acceptably high for both pole counts, and the emf space harmonics content is moderate, the single winding solution seems to be an overall superior solution.

The main condition is to keep the machine saturated for both pole counts. In other words, the airgap flux densities B_{g10} , B'_{g10} on no load for the two pole counts, that is, for the two speeds (in the ratio of p_1/p'_1), have to be about the same:

$$\frac{B_{g10}}{B'_{g10}} = \frac{p_1}{p'_1} \frac{V_1}{V'_1} \frac{K'_{w1} W'_1}{K_{w1} W_1} \quad (4.38)$$

where

V_1 , V'_1 are the phase voltages

W_1 , W'_1 are the turns per phase for the p_1 and p'_1 pole counts

For usual pole changing windings and various winding connections, we have the following [14]:

$$\begin{aligned}\frac{V_1 W_1'}{V_1' W_1} &= 2; & \text{for } YY/Y \\ &= 2.732; & \text{for } Y\Delta/Y \\ &= 2/1.73; & \text{for } YY/\Delta\end{aligned}\quad (4.39)$$

In reality, p_1/p_1' should not be too far away from unity, to avoid needing too large a capacitance, and not too close to unity, to secure a sizable speed regulation range. So, $p_1/p_1' = 1/2$ to $2/3$.

With parallel star/series star combination (Equation 4.39), it is possible to obtain $B_1/B_1' \approx 1$, provided K_{W1}/K'_{W1} makes up for the difference between the p_1/p_1' and $V_1 W_1'/V_1' W_1$ ratios. Balanced three-phase voltages for both pole counts are required. Also, simple pole count switching should be provided to reduce the costs of pole switching.

For a 4/6 pole combination, with 36 slots, the winding in Figure 4.11 [16] provides for $K_{W1} = 0.831$ and $K'_{W1} = 0.644$, the coil pitch being six slots. From Equation 4.38, with YY/Y connection,

$$\frac{(B_{g10})_{2p=4}}{(B'_{g10})_{2p=6}} = \frac{4}{6} \cdot \frac{2 \times 0.644}{0.831} \approx 1 \quad (4.40)$$

In all, two standard power switches are required to power either one or the other of two winding connections.

The typical torque–speed curves for the two pole counts are shown qualitatively in Figure 4.12. The switching from smaller pole count to larger pole count should be made such that the transients before reaching the new steady-state point $0'$ are limited.

A larger slip frequency for peak torque seems to be advantageous from this point of view, at the price of reduced efficiency. An additional capacitor should also help. It is essential that no-load self-excitation conditions be provided at least for one pole count.

Typical voltage vs. speed characteristics for the 4/6 pole counts, obtained with a $2p_1 = 4$ pole, 3.7 kW, 50 Hz, 440 V IM under various phase resistance loads are shown in Figure 4.13 [16]. A rather wide speed range is visible in Figure 4.13, ideally from 1500 rpm to roughly 800 rpm with a single capacitance. A large voltage variation takes place with speed. However, for the cubic speed/power law of wind turbines, the load resistance $R_L = 55 \Omega/\text{phase}$ for $2p_1 = 4$ poles at $n \approx 1500$ rpm leads to $V_L \approx 420$ V at 3238 W, while for $2p_1' = 6$, $R_L = 185 \Omega/\text{phase}$, the SEIG produces 959 W, at the same 420 V and at about 1000 rpm.

Space harmonics are present in the machine, with the subharmonics of two poles for $2p_1' = 6$ pole connection. In general, pole changing windings with $2p_1' = 3K$ are not balanced for harmonics. Terminal voltage unbalance of less than 2 to 3% was observed for $2p_1' = 6$ pole count. Apart from the harmonics problem, the efficiency for the $2p_1' = 6$ pole count is notably lower than that for the $2p_1 = 4$ count.

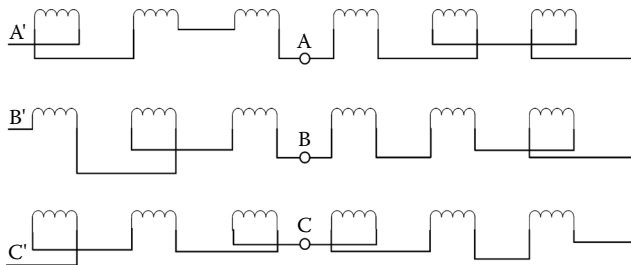


FIGURE 4.11 Stator 4/6 pole combination winding for pole changing self-excited induction generator (SEIG).

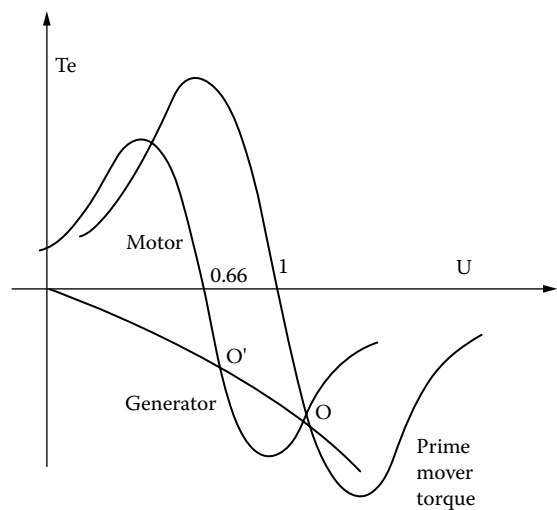


FIGURE 4.12 Torque–speed curves for the 4/6 pole combination.

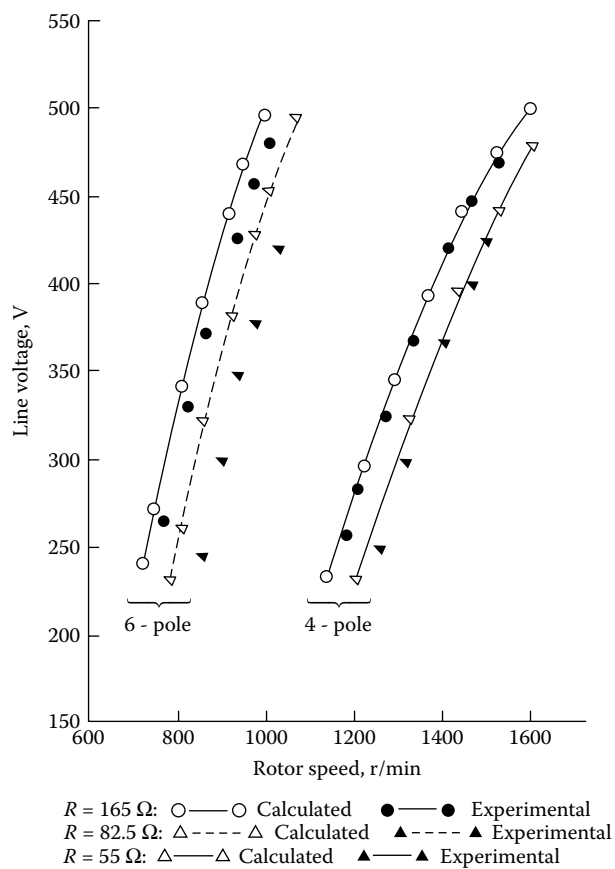


FIGURE 4.13 Line voltage/speed with $C = 100 \mu F$ for a 4/6 pole self-excited induction generator (SEIG).

The reduced cost for variable speed is the main advantage of the pole changing solution, but voltage harmonics, reduced efficiency, and strong transients during pole count switching should also be considered when this solution is applied.

4.7 Unbalanced Operation of Three-Phase SEIGs

Unbalanced phase load impedances or (and) failure of one (or two) capacitors leads to unbalanced operation of SEIGs. Though both Δ and star connections are feasible, only the Δ connection will be treated here in some detail via the method of symmetrical components (Figure 4.14).

The admittance of excitation capacitance (X_c) and load (Z_{ab}^L), Y_{ab} is as follows:

$$\underline{Y}_{ab} = \frac{1}{Z_{ab}^L(f)} + j \frac{f}{X_c} \quad (4.41)$$

Y_{bc} , Y_{ca} have similar expressions.

To solve for the situation in Figure 4.14, first the assumed unbalanced load impedances are replaced by their symmetrical admittances $\underline{Y}^0, \underline{Y}^+, \underline{Y}^-$:

$$\begin{bmatrix} \underline{Y}^0 \\ \underline{Y}^+ \\ \underline{Y}^- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a_1 & a_1^2 \\ 1 & a_1^2 & a_1 \end{bmatrix} \begin{bmatrix} \underline{Y}_{ab} \\ \underline{Y}_{bc} \\ \underline{Y}_{ca} \end{bmatrix} \quad (4.42)$$

The total load plus capacitor currents I_{abL} , I_{bcL} , I_{caL} are also transformed into their symmetric components:

$$\begin{bmatrix} \underline{I}_{abL}^0 \\ \underline{I}_{abL}^+ \\ \underline{I}_{abL}^- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} \underline{Y}^0 & \underline{Y}^- & \underline{Y}^+ \\ \underline{Y}^+ & \underline{Y}^- & \underline{Y}^0 \\ \underline{Y}^- & \underline{Y}^+ & \underline{Y}^0 \end{bmatrix} \begin{bmatrix} \underline{V}_{ab}^0 \\ \underline{V}_{ab}^+ \\ \underline{V}_{ab}^- \end{bmatrix} \quad (4.43)$$

As in the Δ connection, there is no zero voltage sequence, $\underline{V}_{ab}^0$, the components I_a^+ , I_a^- of line currents are as follows:

$$\begin{aligned} \underline{I}_a^+ &= \underline{I}_{abL}^+ - \underline{I}_{caL}^+ = (1-a) \underline{I}_{abL}^+ = (1-a) \left(\underline{Y}^0 \times \underline{V}_{ab}^+ + \underline{Y}^- \times \underline{V}_{ab}^- \right) \\ \underline{I}_a^- &= \underline{I}_{abL}^- - \underline{I}_{caL}^- = (1-a^2) \underline{I}_{abL}^- = (1-a^2) \left(\underline{Y}^+ \times \underline{V}_{ab}^+ + \underline{Y}^0 \times \underline{V}_{ab}^- \right) \end{aligned} \quad (4.44)$$

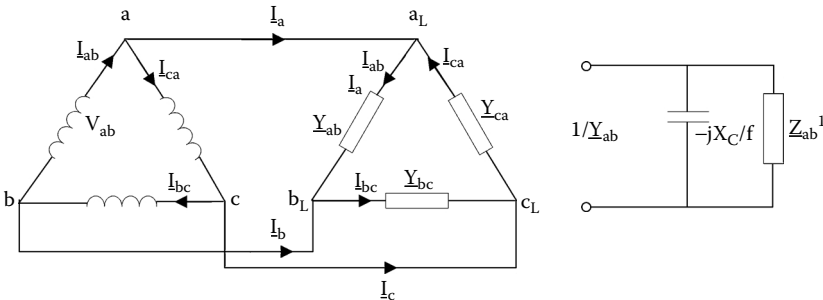


FIGURE 4.14 Δ -Connected self-excited induction generator (SEIG) and load.

On the other hand, the generator current components I_1^+ and I_1^- are as follows:

$$\begin{aligned}\underline{I}_1^+ &= \underline{Y}_G^+ \cdot V_1^+ \\ \underline{I}_1^- &= \underline{Y}_G^- \cdot V_1^-\end{aligned}\quad (4.45)$$

For the load (Equation 4.44), the I_a components I_a^+ , I_a^- as seen from the generator are as follows:

$$\begin{aligned}\underline{I}_a^+ &= (1-a)\underline{I}_{ab}^+ = -(1-a)V_{ab}^+ \underline{Y}_G^+ \\ \underline{I}_a^- &= (1-a^2)\underline{I}_{ab}^- = -(1-a^2)V_{ab}^- \underline{Y}_G^-\end{aligned}\quad (4.46)$$

The generator voltages are considered balanced, and by eliminating V_{ab}^+ and V_{ab}^- after equating Equation 4.44 and Equation 4.46, as they refer to the same currents, the self-excitation condition is obtained as follows:

$$(\underline{Y}_G^+ + \underline{Y}_0)(\underline{Y}_G^- + \underline{Y}_0) - \underline{Y}_+^+ \underline{Y}_-^- = 0 \quad (4.47)$$

Two conditions are contained in Equation 4.47.

The form of Equation 4.47 for balanced operation, that is, for $\underline{Y}_G^+ = \underline{Y}_G^- = \underline{Y}_G$, $\underline{Y}_+ = \underline{Y}_- = \underline{Y}$, $\underline{Y}^0 = 0$, degenerates into the following:

$$\underline{Y}_G - \underline{Y} = 0 \quad (4.47')$$

It is evident that Equation 4.47' is identical to Equation 4.17, obtained for balanced operation. Let us consider the particular case of one phase open (Figure 4.15).

With a single load,

$$\begin{aligned}\underline{Y}_{ab} &= \underline{Y} = \frac{1}{\underline{Z}}; \\ \underline{Y}_{bc} &= \underline{Y}_{ca} = 0\end{aligned}\quad (4.48)$$

So,

$$\underline{Y}^0 = \underline{Y}^+ + \underline{Y}^- = \frac{\underline{Y}}{3} \quad (4.49)$$

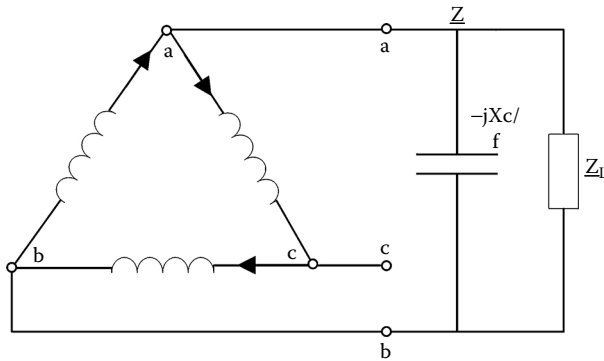


FIGURE 4.15 Δ/Δ connection with one load phase open.

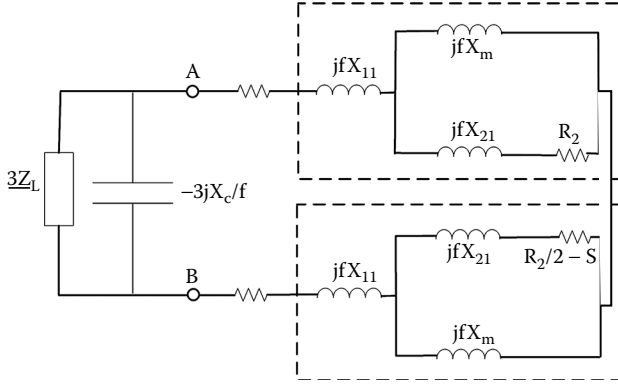


FIGURE 4.16 Δ/Δ -Self-excited induction generator (SEIG) with single capacitor and single load.

The self-excitation condition (Equation 4.47) degenerates into

$$\frac{3}{\underline{Y}} + \frac{1}{\underline{Y}_G^+} + \frac{1}{\underline{Y}_G^-} = 0 \quad (4.50)$$

Equation 4.50 refers to the series connection of positive (+) and negative (−) generator sequence equivalent circuits to $3/\underline{Y} = 3\underline{Z}$ (Figure 4.16).

Other unbalanced situations may be imagined. For example, if phase C opens but the load impedance $\underline{Z}$ remains balanced, the above rationale applies again, but with $Y_{ab} = 1.5 Y$ and $Y_{bc} = Y_{ca} = 0$ [17].

A short-circuit leads to voltage collapse, but at least with induction motor loads, not before notable transients. The computation of performance for unbalanced operation, based on conditions in Equation 4.47, is to be done as for balanced conditions but most probably through optimization methods to solve for frequency f and magnetization reactance X_m simultaneously.

It seems, however, that whenever a zero line current occurs [17], the one-line open magnetization curve is to be applied, at least in the high saturation zone.

Maximum and minimum capacitors for self-excitation for various voltages at given speed and no load may be calculated as for balanced operation. However, efficiency is diminished.

Unbalanced grid operation connections may also lead to unbalanced operation (no capacitor in this case). The absence of capacitors leads to a different approach, but again, the positive and negative components of active and reactive powers are to be calculated.

4.8 One Phase Open at Power Grid

When the IG is connected to the power grid (Figure 4.17), the latter may sometimes be unbalanced [18].

The Z_{G+} , Z_{G-} of the IG are easily recognizable in Figure 4.16, while the symmetrical components of the line voltage V_{ab} , V_{bc} , V_{ca} are as follows:

$$\begin{bmatrix} V^+ \\ V^- \\ V^0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a_1 & a_1^2 \\ 1 & a_1^2 & a_1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \quad (4.51)$$

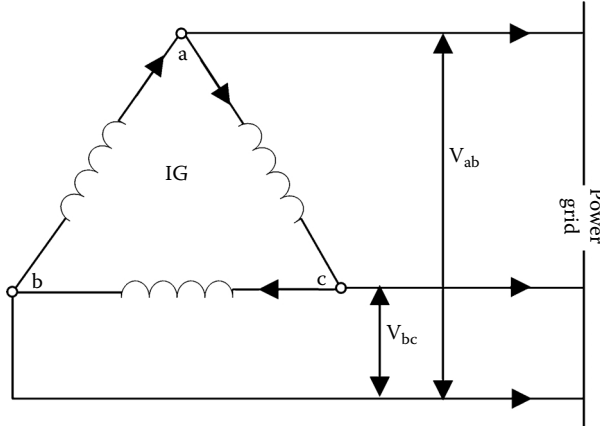


FIGURE 4.17 Induction generator (IG) to power grid.

The equivalent circuit of the IG (positive and negative sequences) connected to the unbalanced power grid (with $V_a^0 = 0$) is shown in Figure 4.18. The input (mechanical) power of IG connected to the power grid P_{input} is as follows:

$$P_{input} = P_{input}^+ + P_{input}^- = -3(I_2^+)^2 \frac{R_2}{S}(1-S) + 3(I_2^-)^2 \frac{R_2}{2-S}(1-S) \quad (4.52)$$

The total IG output active and reactive powers are

$$P_{out} = 3\text{Re}\left(\underline{V}^+ \underline{I}_1^{*+} + \underline{V}^- \underline{I}_1^{*-}\right) \quad (4.53)$$

$$Q_{out} = 3\text{Imag}\left(\underline{V}^+ \underline{I}_1^{*+} + \underline{V}^- \underline{I}_1^{*-}\right) \quad (4.54)$$

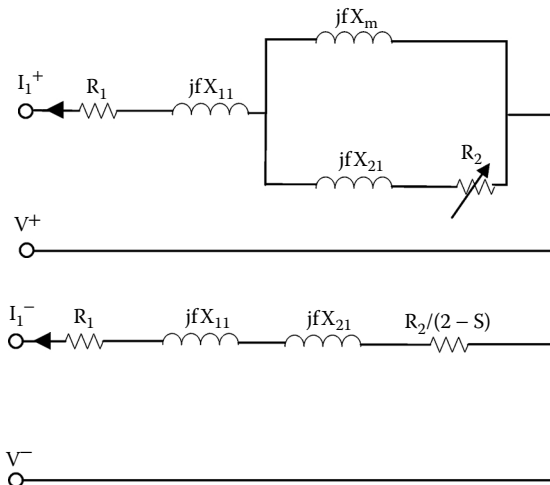


FIGURE 4.18 Sequence equivalent circuit of an induction generator (IG).

The efficiency of the IG connected to the grid η is

$$\eta = \frac{P_{out}}{P_{input}} \quad (4.55)$$

While this represents a solution for the general case, a phase open (say c) represents a probable practical case:

$$\begin{aligned} \underline{I}_{ab} - \underline{I}_{ca} &= \underline{I}_a \\ \underline{I}_{bc} - \underline{I}_{ab} &= \underline{I}_b \\ \underline{I}_{ca} - \underline{I}_{bc} &= \underline{I}_c = 0 \end{aligned} \quad (4.56)$$

The symmetrical components of $\underline{I}_{ab}$, $\underline{I}_{ac}$, $\underline{I}_{ca}$ are

$$\begin{aligned} \underline{I}^+ &= \underline{I}^- \\ \underline{I}_{ab} &= 2\underline{I}^+ \\ \underline{I}_{bc} &= -\underline{I}^- \end{aligned} \quad (4.57)$$

with

$$\underline{V}_{ab} = \underline{V}^+ + \underline{V}^- \quad (4.58)$$

and

$$\begin{aligned} \underline{V}^+ &= \underline{Z}^+ \times \underline{I}_1^+ \\ \underline{V}^- &= \underline{Z}^- \times \underline{I}_1^- \end{aligned} \quad (4.59)$$

$\underline{I}^+$ is

$$\underline{I}^+ = \frac{\underline{V}_{ab}}{\underline{Z}^+ + \underline{Z}^-} \quad (4.60)$$

Based on the data from [Figure 4.18](#) for Z^+ and Z^- the input (mechanical) power P_{input} is as follows:

$$\begin{aligned} P_{input} &= -3I_2^2 K_s R_2 \\ K_s &= \frac{2(1-S)^2}{S(2-S)} \\ I_2^2 &= \frac{\underline{V}_{ab}^2}{(R_{total} + K_s R_2)^2 + X_{total}^2} \\ R_{total} &= 2(R_1 + R_2) \\ X_{total} &= 2(X_{1l} + X_{2l}) \end{aligned} \quad (4.61)$$

Now, with v_{ab} , v_{ca} , v_{bc} given, as amplitude and phase, and known machine parameters, ω_1 and given speed ω_p , the slip S may first be calculated as follows:

$$S = \frac{\omega_1 - \omega_r}{\omega_1} \quad (4.62)$$

Then, the values of K_s , I_2 , P_{input} are determined. Then I_1^+ , I_1^- and I_1 and V^+ , V^- , P_{out} , Q_{out} are computed. That is, steady-state performance vs. slip may be calculated for various degrees of grid voltage unbalance V^-/V^+ , for example. Both the reactive power drawn from the power grid and IG losses increase with input power.

The increasing of grid voltage unbalance leads to increased currents, losses, and power factor reduction for given slip. The current also depends on how the voltage unbalance is produced: by one increased or by one reduced voltage.

A small voltage unbalance has a large impact on the IG currents. For the same total losses, the output power is reduced considerably with respect to balanced operation. For 10% voltage unbalance, it may be allowed to handle only 30 to 40% of rated power at an acceptable temperature level.

Derating in direct relationship to voltage unbalance V^-/V^+ ratio is recommended in order to avoid IG overheating.

4.9 Three-Phase SEIG with Single-Phase Output

Single-phase output SEIGs may be approached with a two-phase induction generator as shown in the next paragraph. However, the power density, power pulsations, vibration and noise, are notable. Also, when the power level goes above 2 to 3 kW, the single-phase IG becomes less attractive and is not available off the shelf.

Making use of a three-phase IG, with an advanced degree of phase symmetrization, may prove a practical solution for single-phase output, at least above 2 to 3 kW per unit. Three main connections were proposed:

- Steinmetz connection (Figure 4.19a) [19]
- Smith connection (Figure 4.19b) [20]
- Fukami connection (Figure 4.19c) [21]

All connections are, in principle, capable of providing machine symmetrization at some speed (load) for given frequency and perform with good efficiency and power factor for a notable power range. However, it seems that the Steinmetz connection, augmented with series compensation (C_s), does better with only two capacitors that are wisely used (at high voltage level): about 2.0 P.U. power delivery with limited voltage self-regulation.

Consequently, we will treat here in detail only the Steinmetz connection with series compensation [19].

For steady state, again, the method of symmetrical components is applied. The connection in Figure 4.19a suggests the following relationships:

$$\underline{V} = \underline{V}_a \quad (4.63)$$

$$\underline{V}_a + \underline{V}_b + \underline{V}_c = 0$$

$$\underline{I}_1 = \underline{V}_b \cdot \underline{Y}_{Cp} = \underline{I}_c - \underline{I}_b \quad (4.64)$$

$$\underline{I} = \underline{I}_a - \underline{I}_c \quad (4.65)$$

where $\underline{Y}_{Cp}$ is the admittance of the parallel capacitance:

$$\underline{Y}_{Cp} = jX_{cp}^{-1}f; \quad f \text{ is P.U. frequency} \quad (4.66)$$

The symmetrical components of voltages in Equation 4.51 with Equation 4.63 through Equation 4.65 are as follows:

$$\underline{V}^+ = \frac{V\sqrt{3}\left(\underline{Y}_G^- + \frac{e}{\sqrt{3}} \frac{j\pi/6}{\sqrt{3}} \underline{Y}_{Cp}\right)}{\underline{Y}_{Cp} + \underline{Y}_G^+ + \underline{Y}_G^-} \quad (4.67)$$

$$\underline{V}^- = \frac{V\sqrt{3}\left(\underline{Y}_G^+ + \frac{e}{\sqrt{3}} \frac{-j\pi/6}{\sqrt{3}} \underline{Y}_{Cp}\right)}{\underline{Y}_{Cp} + \underline{Y}_G^+ + \underline{Y}_G^-}$$

where $\underline{Y}_{G+}$ and $\underline{Y}_{G-}$ are positive and negative sequence admittances of IG at P.U. frequency f (Figure 4.16):

$$\frac{1}{\underline{Z}_{AB}} = \underline{Y}_G^+ \quad (4.68)$$

$$\frac{1}{\underline{Z}_{BC}} = \underline{Y}_G^-$$

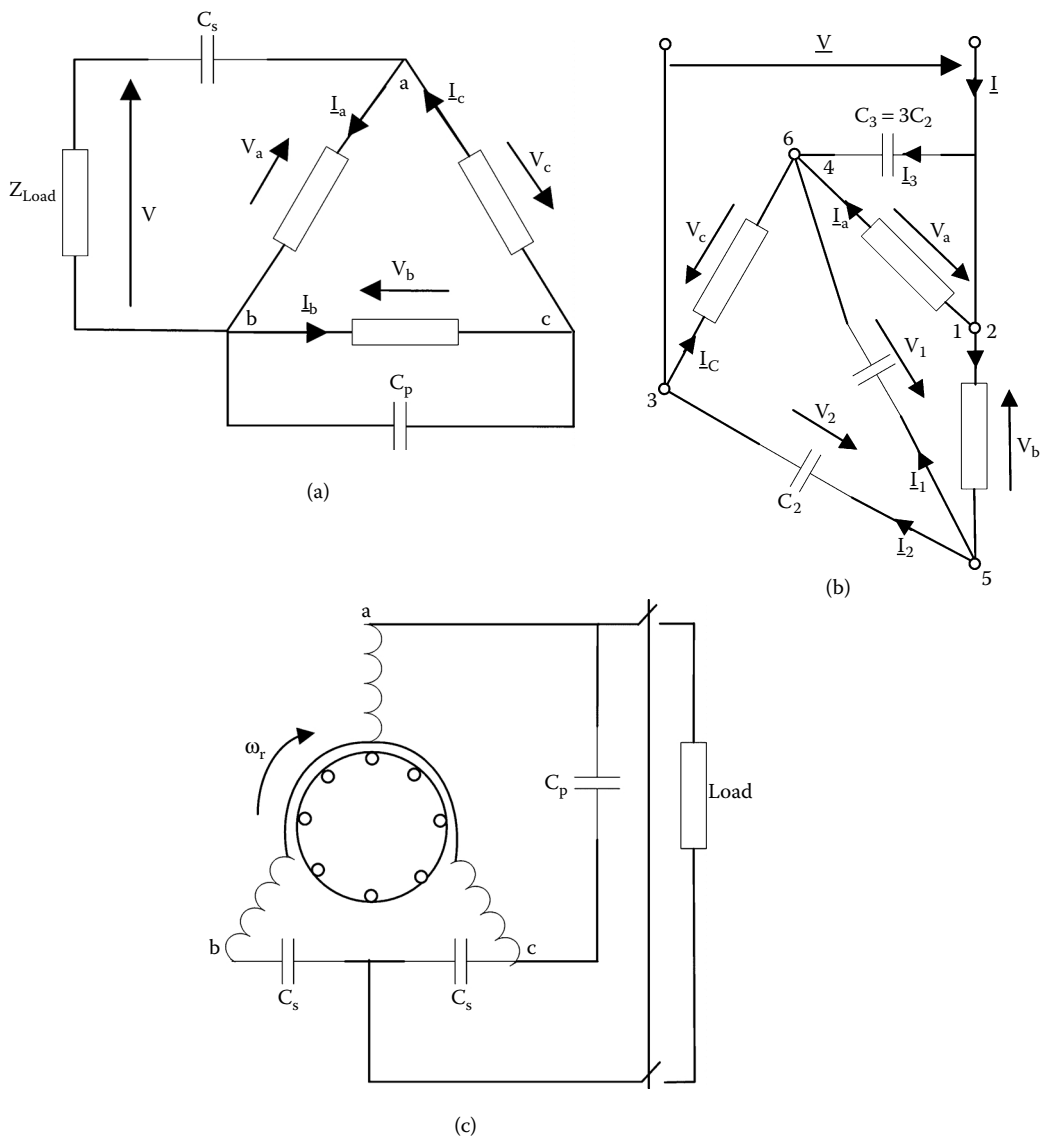


FIGURE 4.19 Three-phase self-excited induction generator (SEIG) with single-phase output: (a) Steinmetz connection, (b) Smith connection, and (c) Fukami connection.

The equivalent IG impedance at points a, b , $\underline{Z}_{IG}$, is as follows:

$$\underline{Z}_{IG} = \frac{\underline{Z}_G^+ \underline{Z}_G^- + \underline{Z}_G^+ \underline{Z}_{Cp} + \underline{Z}_G^- \underline{Z}_{Cp}}{3 \underline{Z}_{Cp} + \underline{Z}_G^+ + \underline{Z}_G^-} \tag{4.69}$$

The sum of impedances $\underline{Z}_{IG}$, $\underline{Z}_{CS}$, and $\underline{Z}_L$ should be zero for self-excitation:

$$\begin{aligned} \underline{Z}_{IG} + \underline{Z}_L + \underline{Z}_{CS} &= 0 \\ \underline{Z}_{CS} &= -j \frac{X_{CS}}{f} \end{aligned} \tag{4.70}$$

The load impedance $\underline{Z}_L$ (at P.U. frequency f) is

$$\underline{Z}_L = R_L + j \left(fX_L - \frac{X_{LC}}{f} \right) \quad (4.71)$$

For the impedance model solution, the frequency f and reactance X_m are the unknowns, to be solved for iteratively from Equation 4.70.

The complexity of $\underline{Z}_G^+$ and $\underline{Z}_G^-$ leaves little room for an analytical solution.

It is practical to calculate the amplitude of the complex impedance in Equation 4.70 and to force it to zero, that is, to find a minimum by an optimization method (Hooke–Jeeves for example [19]):

$$Z(f, X_m) = \sqrt{(R_{IG}(f, X_m) + R_L)^2 + \left(X_{IG}(f, X_m) + fX_L - \frac{X_{CL}}{f} - \frac{X_{CS}}{f} \right)^2} = 0 \quad (4.72)$$

The unsaturated value of X_m , X_{max} may be taken as an initial value of $X_m(1)$ or as a constraint. Again, the compensation ratio K is defined as $K = X_{cs}/X_{cp}$. As K increases, in general, the voltage reduction with load is decreased. Values of $K \approx 0.3$ to 0.5 seem to be practical (as for the three-phase balanced SEIG in the previous paragraph).

For a 2.2 kW, four-pole, 220 V, 50 Hz, 9.4 A IM with $R_1 = 0.0844$ P.U., $X_{l1} = 0.112$ P.U., $R_2 = 0.098$ P.U., $X_{l2} = 0.1$ P.U., $R_m = 2.2$ P.U., and $E_1(X_m)$ as in Equation 11.29, the load voltage vs. load current for $PF = 1.0$, $K = 0.34$ speed $U = 1$ is shown in Figure 4.20a and the power in Figure 4.20b [19].

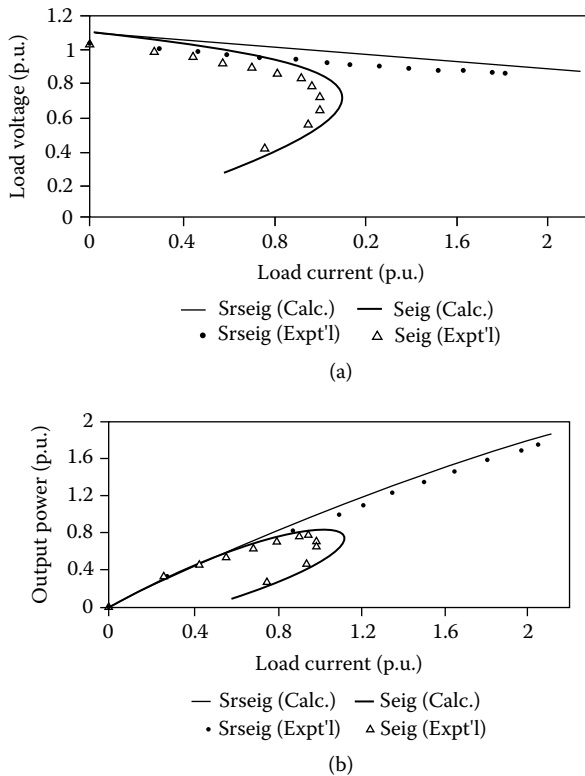


FIGURE 4.20 (a) Voltage and (b) output power vs. load in per unit (P.U.).

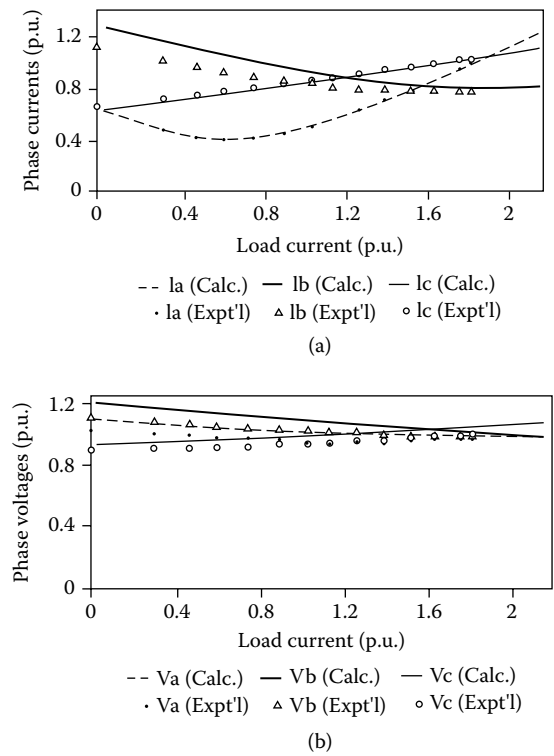


FIGURE 4.21 (a) Phase currents and (b) voltages vs. load in per unit (P.U.) for $PF = 1.0$.

The extension of the stability zone due to the series compensation is spectacular. As expected, purely balanced operation is hardly present, but the phase current and voltage unbalances (Figure 4.21a and Figure 4.21b) are acceptable. The efficiency is rather large for a wide range of loads (Figure 4.22) [19].

In Figure 4.20, Figure 4.21, and Figure 4.22, SEIG means without series compensation, and SRSEIG means with series compensation ($K = 0.34$, $C_p = 125 \mu F$, $C_s = 370 \mu F$).

As evident from Figure 4.20, Figure 4.21, and Figure 4.22, the largest phase voltage is below 1.2 P.U., which is an acceptable value.

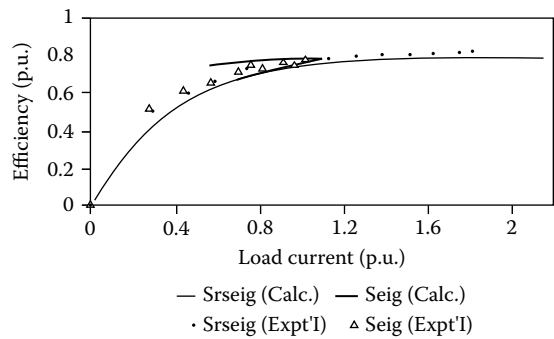


FIGURE 4.22 Efficiency vs. load in per unit (P.U.).

The phase voltages are almost symmetric at 1.6 P.U. load, while below and above that load, a certain degree of unbalance remains.

The increase in output power to 2.0 P.U. with the Steinmetz connection and series compensation may make it a practical solution, for powers above 3 kW, where single-phase IMs are not available off the shelf.

4.10 Two-Phase SEIGs with Single-Phase Output

As already mentioned, two-phase induction machines may also be used as SEIGs with single-phase output. The self-regulated such configuration contains a self-excitation capacitor C_e placed in parallel with the excitation (additional) stator winding, while the power winding is provided with a single series capacitor C_s or with a long- or short-shunt capacitor C_p (Figure 4.23).

The configuration with only two capacitors C_e and C_s will be considered further here (for the others, see the literature [22, 23, 24]), as it seems a good compromise between capacitor costs and performance.

To investigate the steady state, the symmetrical component method is used again. We should notice the following:

- The excitation capacitor C_e may be lumped in series with the excitation winding, which is short-circuited ($V_a = 0$).
- The series compensation capacitor C_s may be lumped into the load Z'_L :

$$\underline{Z}'_L(f) = \underline{Z}_L(f) - j \frac{X_{CS}}{f} \quad (4.73)$$

For an R_L, L_L load,

$$\underline{Z}_L(f) = R_L + jfX_L \quad (4.74)$$

As the excitation voltage $V_a = 0$ and $V_m = V_s$, the positive and negative sequence voltages are as follows:

$$\underline{V}_m^+ = \underline{V}_m^- = \underline{V}_s/2 = -\underline{Z}'_L(\underline{I}_m^+ + \underline{I}_m^-)/2 \quad (4.75)$$

The equivalent circuit in positive and negative components of the two-phase machine (Reference [1], p. 830) may be slightly simplified, as the voltage $\underline{V}_m^+$ and $\underline{V}_m^-$ (4.75) may be written as follows:

$$\begin{aligned} \underline{V}_{AB} = \underline{V}_m^+ &= + \frac{\underline{Z}'_L}{2} (\underline{I}_m^+ - \underline{I}_m') - \underline{Z}'_L \underline{I}_m^+ \\ \underline{V}_{BC} = \underline{V}_m^- &= -\underline{Z}'_L \underline{I}_m^- - \frac{\underline{Z}'_L}{2} (\underline{I}_m^+ - \underline{I}_m') \end{aligned} \quad (4.76)$$

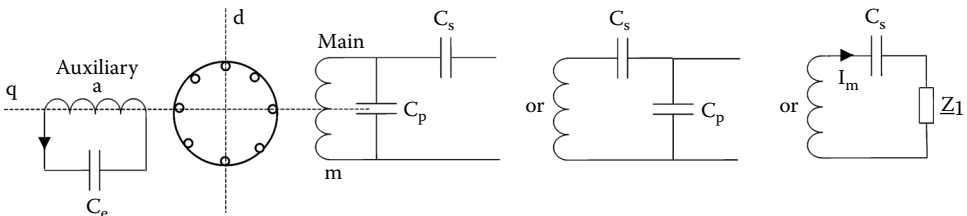


FIGURE 4.23 Two-phase self-excited induction generator (SEIG) configurations with single-phase output.

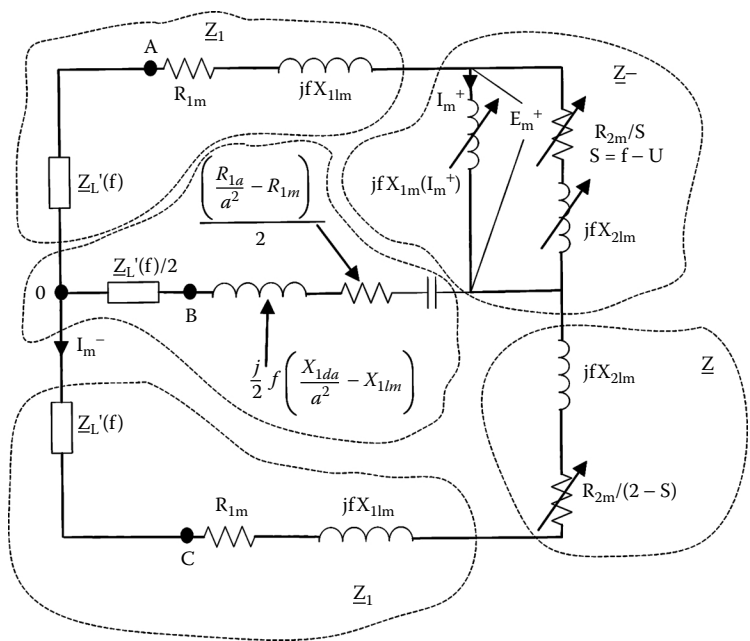


FIGURE 4.24 The equivalent circuit of a two-phase self-excited induction generator (SEIG) with single-phase output.

This way the complete equivalent circuit of the two-phase machine with unequal windings is shown in Figure 4.24.

Notice that “*a*” is the turn ratio between the auxiliary excitation and main power winding. This allows for the design with a different voltage in the excitation winding and also introduces one more variable for symmetrization at a desired load.

The equivalent circuit in Figure 4.24 may be reduced easily to the one in Figure 4.25a and Figure 4.25b.

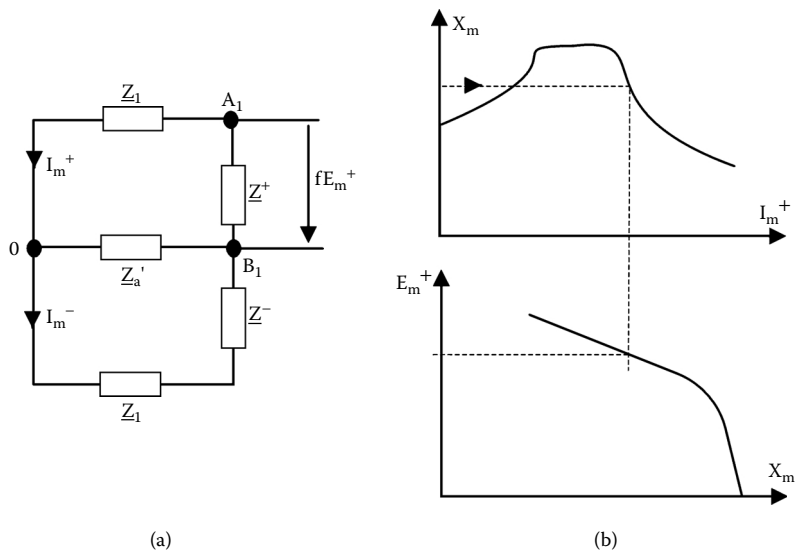


FIGURE 4.25 (a) Simplified equivalent circuit of a two-phase self-excited induction generator (SEIG) and (b) magnetization curves.

The self-excitation condition is evident: the summation of currents in the node 0 has to be zero:

$$\underline{Y}_E = \frac{1}{\underline{Z}_1 + \underline{Z}_+} + \frac{1}{\underline{Z}_1 + \underline{Z}^-} + \frac{1}{\underline{Z}'_a} = 0 \quad (4.77)$$

All parameters in Equation 4.77 depend on frequency f , but only X_m is dependent on I_m^+ . So, again, we have two variables. Optimization methods to minimize (make it zero) the amplitude of the admittance in Equation 4.77 would be a fairly straightforward way to solve for both f and X_m with given speed (slip S) and other IG load parameters and capacitors.

The magnetization reactance X_m is a function of the positive sequence magnetization current I_m^+ , and the relationship $V_{AB} = E_m^+(I_m^+)$ is to be known from measurements or through computation (in the design stage). Once X_m and f are known, from the magnetization curve $X_m(I_m^+)$, the value of I_m^+ is calculated. Further on, the airgap voltage fE_m^+ is determined:

$$fE_m^+ = V_{A_1B_1} = fX_m I_m^+ \quad (4.78)$$

From now on, the equivalent circuit in [Figure e 4.25a](#) and [Figure e 4.25b](#) may be used to calculate the following:

$$I_m^+ = fE_m^+ \frac{1}{\underline{Z}_1 + \frac{(\underline{Z}'_a \cdot \underline{Z}_1)}{\underline{Z}'_a + \underline{Z}_1}} \quad (4.79)$$

$$\underline{I}_m^- = \underline{I}_m^+ \cdot \frac{\underline{Z}'_a}{\underline{Z}^- + \underline{Z}_1} \quad (4.80)$$

The load current $\underline{I}$ is simply

$$\underline{I} = \underline{I}_m^+ + \underline{I}_m^- \quad (4.81)$$

The excitation current $\underline{I}_a$ is

$$\underline{I}_a = j(\underline{I}_m^+ - \underline{I}_m^-) \quad (4.82)$$

It is evident that symmetrization is obtained when $\underline{I}_m^- = 0$.

The output electrical power P_{out} is

$$P_{out} = R_L I_m^2 \quad (4.83)$$

The positive sequence rotor current I_{2m}^+ (from [Figure 4.24](#)) is as follows:

$$\underline{I}_{2m}^+ = \underline{I}_m^+ \frac{jfX_{1m}}{\frac{R_{2m}}{S} + jf(X_{1m} + X_{2m})} \quad (4.84)$$

Neglecting the mechanical losses, the input (shaft) power P_m is

$$P_m = 2 \left[(I_{2m}^+)^2 \frac{R_{2m}}{S} - (I_{2m}^-)^2 \frac{R_{2m}}{2-S} \right] (1-S) \quad (4.85)$$

The negative sequence power is translated into losses.

To calculate the efficiency, the core losses p_{iron} and the mechanical losses p_{mec} have to be added.

$$\eta = \frac{P_{out}}{P_m + P_{iron} + P_{mec}} \quad (4.86)$$

The generator voltage V is as follows (Equation 4.75):

$$\underline{V}_{Gen} = -Z'_L \underline{I}_m \quad (4.87)$$

The load voltage V_{load} differs from V_{Gen} by the voltage drop along the series capacitor C_s :

$$\underline{V}_{load} = \underline{V}_{Gen} + j \frac{X_c}{f} \underline{I}_m \quad (4.88)$$

The above model may be instrumental, after arranging it into a computer program, in calculating the steady-state performance for given speed, capacitors, and load impedance. Changing the load impedance will produce data for steady-state characteristics.

For a 700 W, 50 Hz, $2p_1 = 2$ poles, $V_N = 230$ V machine with $R_{1m} = 3.94 \Omega$, $R_{sa} = 4.39 \Omega$, $R_{2m} = 3.36 \Omega$, $X_{1lm} = X_{2lm} = 5.48 \Omega$, $X_{1la} = 7.5 \Omega$, unsaturated $X_{1m} = 70 \Omega$ and $C_e = 40 \mu\text{F}$, $C_s = 100 \mu\text{F}$, load voltage vs. current curves are shown in Figure 4.26 [25].

The beneficial effect of the series compensation by C_s is evident. The symmetrization problem remains, but, beside C_s and C_e , the turns ratio a is a variable to take advantage of in the design optimization process.

For powers below 3 kW, where the two-phase induction machine is available, its use as a generator still seems to be a practical option in low-cost applications.

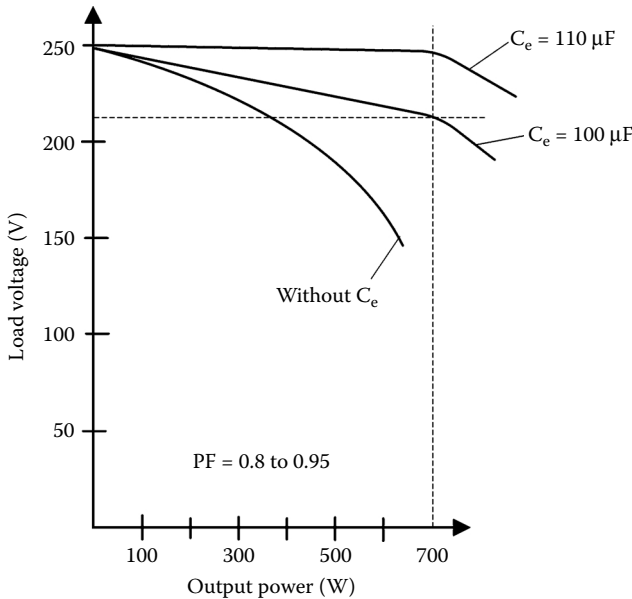


FIGURE 4.26 Load voltage vs. output power.

4.11 Three-Phase SEIG Transients

SEIGs undergo transients on no load during self-excitation, when electrical load is connected or rejected or varied. When speed is modified or the self-excitation capacitor is varied with load to control the load voltage, transients also occur.

The method of approach to SEIG transients is the d - q (space-phasor) model. We will use here the space-phasor model, as it facilitates the accountance of magnetic saturation. The space-phasor model of the induction machine in stator coordinates (see Chapter 2) is as follows:

$$\begin{aligned}\bar{V}_1 &= -R_1 \bar{I}_1 - \frac{d\bar{\Psi}_1}{dt} \\ \bar{\Psi}_1 &= L_{1l} \cdot \bar{I}_1 + \bar{\Psi}_m\end{aligned}\quad (4.89)$$

$$\begin{aligned}0 &= -R_2 \bar{I}_2 - \frac{d\bar{\Psi}_2}{dt} + j\omega_r \bar{\Psi}_2 \\ \bar{\Psi}_2 &= L_{2l} \cdot \bar{I}_2 + \bar{\Psi}_m\end{aligned}\quad (4.90)$$

The association of signs corresponds to generating mode. The magnetizing (airgap) Ψ_m is

$$\begin{aligned}\bar{\Psi}_m &= L_m(I_m) \bar{I}_m; \\ \bar{I}_m &= \bar{I}_1 + \bar{I}_2\end{aligned}\quad (4.91)$$

The $L_m(I_m)$ function is obtained from tests or through computation in the design stage.

The electromagnetic torque T_e is

$$T_e = \frac{3}{2} p_1 \text{Imag} \left(\bar{\Psi}_1 \bar{I}_1^* \right) \quad (4.92)$$

The capacitors connected at the terminals ($C_Y = 3C_\Delta$) lead to the voltage equation:

$$\frac{d\bar{V}_1}{dt} = \frac{1}{C_Y} \cdot \bar{I}_C \quad (4.93)$$

The generator motion equation is written as follows:

$$J \frac{d\omega_r}{dt} = T_{\text{prime_mover}} - T_e \quad (4.94)$$

The dynamics of the turbine with its speed control model (if any) that drives the SEIG should be added here.

With the flux linkages as variables and the currents as dummy variables, only the $L_m(I_m)$ function needs to be known to account for magnetic saturation. The decomposition into d - q components to deal with “real number variables” is straightforward, as $(\bar{V}_1 = \bar{V}_d + j\bar{V}_q)$.

A passive load may be described as follows:

$$\begin{aligned}\bar{V}_1 &= R_L \bar{I}_L + L_L \frac{d\bar{I}_L}{dt} + \bar{V}_{CL} \\ \frac{d\bar{V}_{CL}}{dt} &= \frac{1}{C_{YL}} \bar{I}_L \\ \bar{I}_L &= \bar{I}_1 - \bar{I}_C\end{aligned}\quad (4.95)$$

On the other hand, an induction motor load may be described as

$$\begin{aligned}\bar{V}_1 &= R_{1M} \bar{I}_M + \frac{d\bar{\Psi}_{1M}}{dt} \\ 0 &= R_{2M} \bar{I}_{2M} + \frac{d\bar{\Psi}_{2M}}{dt} - j\omega_{rM} \bar{\Psi}_{2M} \\ \bar{\Psi}_{1M} &= L_{1M} \bar{I}_{1M} + \bar{\Psi}_{mM} \\ \bar{\Psi}_{2M} &= L_{2M} \bar{I}_{2M} + \bar{\Psi}_{mM} \\ \bar{\Psi}_{mM} &= L_{mM} (\bar{I}_{1M} + \bar{I}_{2M}) \\ T_{eM} &= \frac{3}{2} p_1 \text{Imag} \left(\bar{\Psi}_{1M} \bar{I}_{1M}^* \right) \\ J_M \frac{d\omega_{rM}}{dt} &= T_{eM} - T_{Load}\end{aligned}\quad (4.96)$$

The same models could also be used in synchronous coordinates, but then the currents and voltages are transformed back into stator coordinates.

Typical transients for a 1.1 kW, 127/220 V, 8.3/4.8 A line current, 60 Hz, two-pole machine with $R_1 = 0.078$ P.U., $X_{11} = X_{21} = 0.0895$ P.U. are shown in what follows [25].

The rather slow phase *a* voltage buildup at no load for $\omega_r = 3600$ rpm and $C_\Delta = 248.7$ μ F is evident in Figure 4.27. Sudden connection of a resistive load ($R_L = 80$ Ω), $t = 0.4$ sec shows a mild reduction of phase

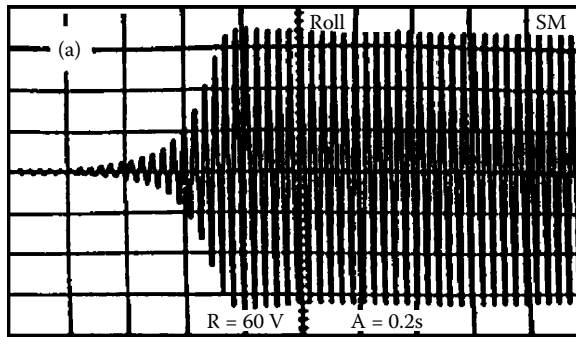


FIGURE 4.27 Voltage buildup at no load.

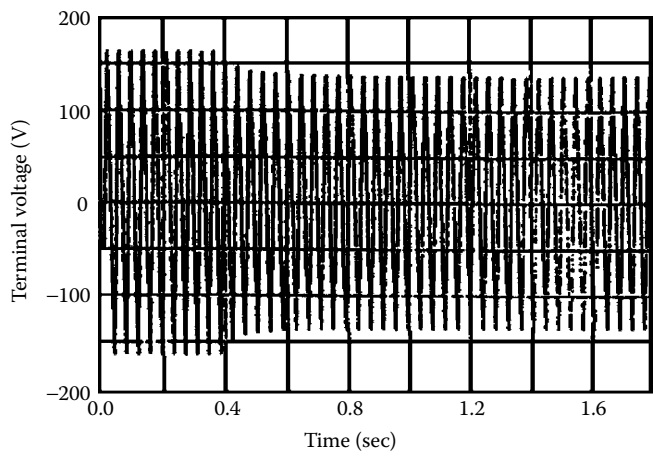


FIGURE 4.28 Sudden connection of resistive load.

a voltage with stable response (Figure 4.28), as the load is not too large. A step loading from $R_L = 80$ to $10\ \Omega$ leads to voltage collapse [25]. A notable voltage increase occurs when the resistive load is rejected (Figure 4.29).

A few remarks are in order:

- Sudden application of load — be it R_L or R_L, L_L — leads to fast voltage reduction at the SEIG terminals, while RC load leads to very small voltage variation.
- The sudden disconnection of the capacitor leads to quick decay of terminal voltage to zero.
- Load rejection leads to stable voltage recovery toward the no-load steady state (for constant speed).

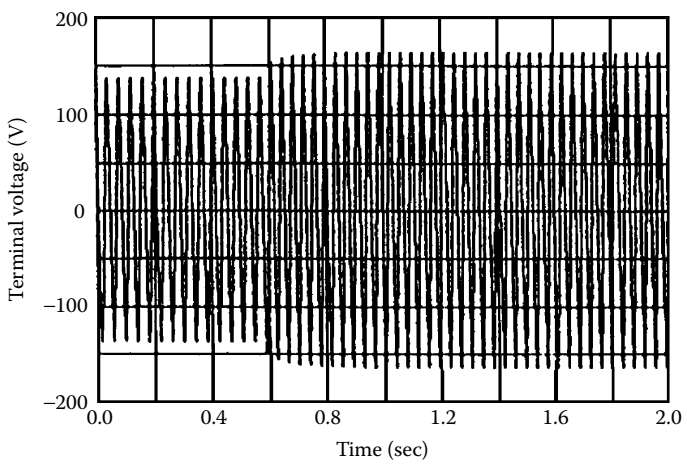


FIGURE 4.29 Resistive load rejection at 0.58 sec ($R_L = 80\ \Omega$).

- When the load is greatly increased, the voltage of the machine collapses, as the SEIG de-excites and thus desaturates rapidly.
- A short-circuit at SEIG terminals may cause up to 2.0 P.U. voltage surges and 5 P.U. current transients for a short period of around 20 msec before the voltage collapses.
- An SEIG supplying an induction motor load requires large capacitances to cover for the motor reactive power. However, when the motor is disconnected, the large capacitance may produce overvoltages that are too large. It is, thus, practical to divide the capacitances between the SEIG and the induction motor (IM) [26]. For safe starting of an IM, the SEIG-to-IM power ratio should be at least 1/0.6, but, to handle stably up to 100% step mechanical load, the power ratio should be 3(4) to 1.

4.12 Parallel Connection of SEIGs

As there are constraints on SEIG ratings per unit for microhydro or wind turbines, several such SEIGs may have to be operated in parallel with a single capacitance bank C (Figure 4.30) for self-excitation.

As one of the main problems with SEIGs is their poor voltage regulation, improvements may be obtained by capacitor variation or (and) speed variation of some SEIGs of the group, as is done for single such generators operating on autonomous load.

For self-excitation, at node 0 (Figure 4.30), the total admittance has to be zero. All generators have the same terminal voltage and frequency f (P.U.).

On the other hand, the summation of currents in the n generators is as follows:

$$\sum_{i=1}^n I_{li} = V_1 \left(\frac{1}{R_L} - \frac{j}{fX_L} + \frac{jf}{X_C} \right) \quad (4.97)$$

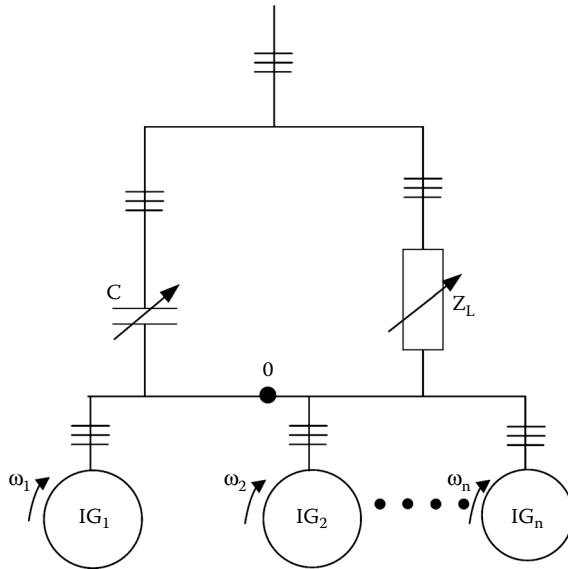


FIGURE 4.30 Self-excited induction generators (SEIGs) in parallel.

In Equation 4.97, an additional variable inductance (X_L) is placed in parallel with the fixed excitation capacitor (X_C) to vary the total equivalent capacitor. Ballast resistive load is used to control the IG group when the load decreases.

Also, for each generator, from the equivalent circuit,

$$\begin{aligned} I_{Li} &= -\frac{V_1}{Z_{Gi}}; \\ I_{Li} + I_{mi} &= I_{2i} = \frac{-f E_{Li}}{\frac{R_{2i}}{s_i} + jf X_{2i}} \end{aligned} \quad (4.98)$$

The airgap emf E_{Li} depends on the magnetization reactance X_{mi} , as already discussed extensively earlier in this chapter.

The self-excitation condition is, thus, from Equation 4.97,

$$Y_t = \sum_{i=1}^n \frac{1}{Z_{Gi}(f)} + \frac{1}{R_L} - \frac{j}{fX_L} + \frac{jf}{X_C} = 0 \quad (4.99)$$

Equation 4.97 through Equation 4.99 provide for $n + 2$ unknowns, X_{mi} , and C and f . Various iterative procedures such as Newton–Raphson’s may be used to solve such a problem [27]. The voltage V_1 , all parameters, and speeds are given. Initial values of variables are given and then adjusted until good convergence is obtained.

As expected, for given voltage, the required capacitance increases with load. The frequency f drops when the load increases. For a fixed load power, the frequency f increases, as the voltage increases, as for single SEIGs. Also, lagging power factor loads require larger capacitance for given voltage and load power. Increasing the number of identical SEIGs for the same load power tends to require more capacitance at given voltage. The frequency increases in such a case as the load of each SEIG is decreased.

The machine speeds u_1 and u_2 also influence the performance (Figure 4.31) [27]. The capacitance increases with decreasing speed and so does the frequency for given voltage and load power. The load

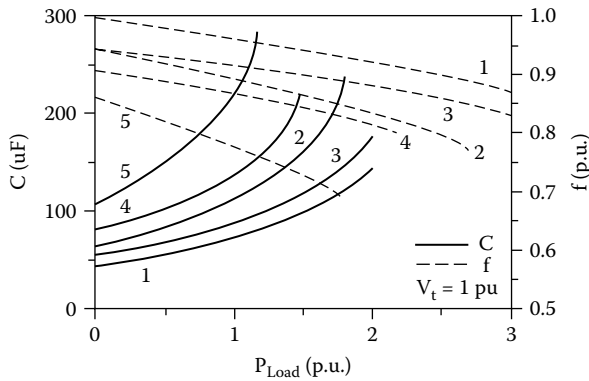


FIGURE 4.31 Influence of self-excited induction generator (SEIG) speeds (in P.U.) on required capacitance C and on frequency f .

power factor also influences the required speed for given capacitor and voltage. The speed and frequency increase with load and more so with lagging power factor loads.

Again, as for single SEIGs, voltage control of frequency insensitive loads may best be accomplished by combining capacitance and speed control. In this case, the frequency variation is also limited.

Note that the parallel operation of an SEIG may be approached through the d - q model, valid for transients and steady state. The eigenvalue method is then to be applied to predict the system's behavior and to determine the capacitance values [28].

4.13 Connection Transients in Cage Rotor Induction Generators at Power Grid

Rigid as they may seem, cage rotor induction generators are still connected, up to some power level per unit, directly to the power grid. Adjustments in its power delivery are made by controlling the turbine speed (torque). The direct connection of a cage rotor induction machine to a strong power grid leads, irrespective of machine initial speed, to large current and torque transients. When the induction machine rating increases, or (and) the local power grid is not so strong, the disturbances produced by such large transients are severe. Moreover, the torque transients are so large that they can, in time, damage the turbine.

If the simplicity and low costs of cage rotor IGs are to keep this solution in perspective, besides speed (small range) control, the switch-on (off) transients to the power grid have to be drastically reduced. To accomplish such a goal, with limited expense, it seems that either soft-starters or additional resistors should be connected in series with the stator windings for a short period of time (a few seconds). For wind turbines as prime movers, rotor wind and hub wind speeds (in m/sec) vary continuously with time (Figure 4.32a) [29]. The wind turbine generator scheme is shown in Figure 4.32b.

In a direct start transient simulation, using the d - q model, a four-pole 0.5 MW IG transmission model response (Figure 4.33) shows aerodynamic torque, mechanical torque, turbine rotor speed, and generator rotor speed. Some small oscillations are visible in the turbine rotor speed but hardly so in the generator rotor speed [29].

For the same IG, accelerated freely by the wind turbine up to 1500 rpm and then directly connected to the grid, the speed, phase current amplitude, and reactive and active power transients for some loading are shown in Figure 4.34 [29]. There is a very short-lived superhigh peak in phase current (up to 10 P.U.) and in reactive and active power. Then, they all stabilize but still retain some small pulsations due to wind turbine speed pulsations (Figure 4.34).

The power grid was realistically modeled [29].

The connection to the power grid of larger power IGs (say 2 MW) poses problems of voltage and too large current transients. This is why soft-starters were proposed for the scope. They may also automatically disconnect the generator when there is not enough wind power and reconnect again based on the power factor of IG, which varies notably with the slip.

A typical start-up to 1500 rpm and then connection and loading of a 2 MW, four-pole IG through a soft-starter is illustrated in Figure 4.35 [29]. The current peaks are still above the rated value but are much less than those for direct connection to the grid. The same is true for reactive and active power transients at the price of slower speed stabilization to load (1.8 MW).

A capacitance bank controlled in steps may be used to compensate for the IG reactive power (of about 0.936 MVAR for 1.8 MW) and keep the voltage regulation within limits when load varies in the local grid. Alternatively, an external resistor may be used to reduce the grid connection transients (Figure 4.36) [30]. The resistor connection procedure is shown to perform well with respect to all three connection factors:

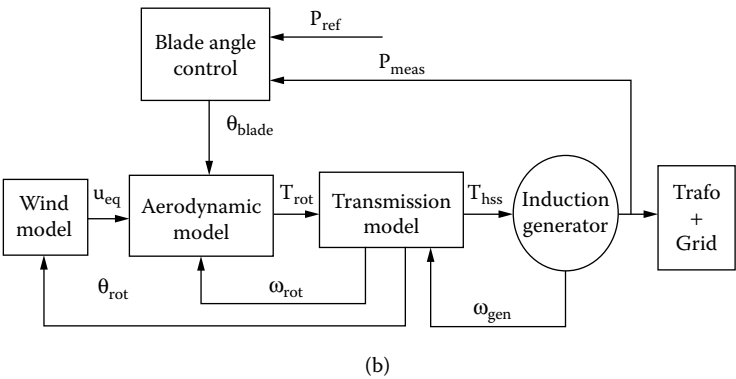
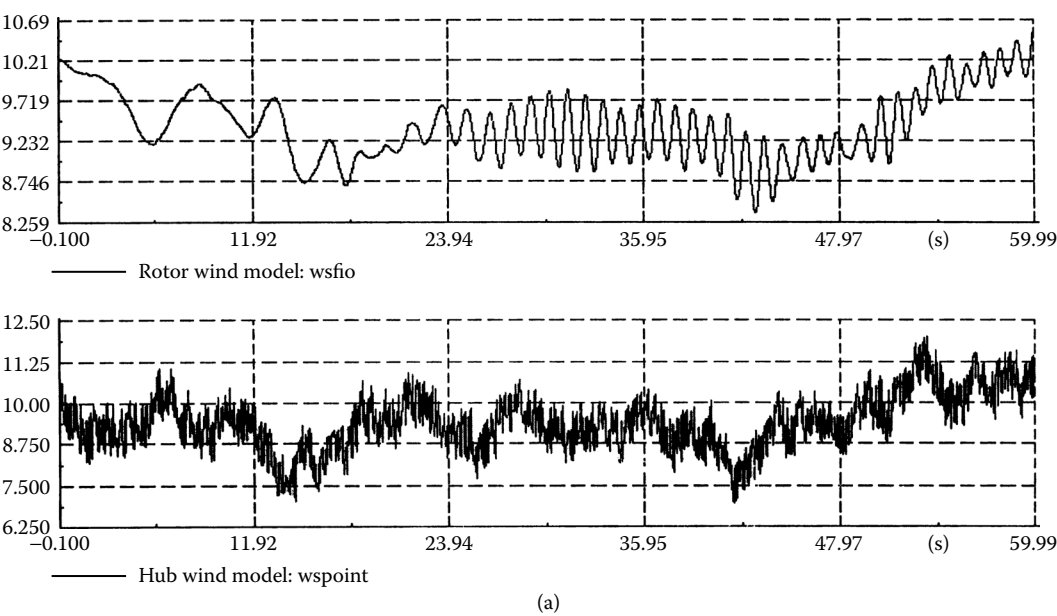


FIGURE 4.32 (a) Rotor wind and hub wind model and (b) wind turbine model.

- Maximum voltage change factor K_u
- Maximum current factor K_i
- Flicker step factor K_f [31]

A voltage change factor of only 4% is now enforced in Europe at the IG connection to the grid. Active stall wind turbine regulation is standard for the smooth connection of megawatt (MW)-size wind induction generators. A variable slip IG may also be used, when the IG has a wound rotor and a controlled or self-controlled rotor connected additional resistor. Figure 4.37 shows 15 kW, 0.8% slip active-stall regulated IG connection to the grid at no load. The external stator resistance is $R_{ext} = 50R_1 = 1.8 \Omega$ [30]. A very smooth connection is evident. The costs of the short-lived current external resistance is quite small in comparison with the soft-starter, while fulfilling the smooth connection conditions, as the reactive power requirements are nonzero for a soft-starter.

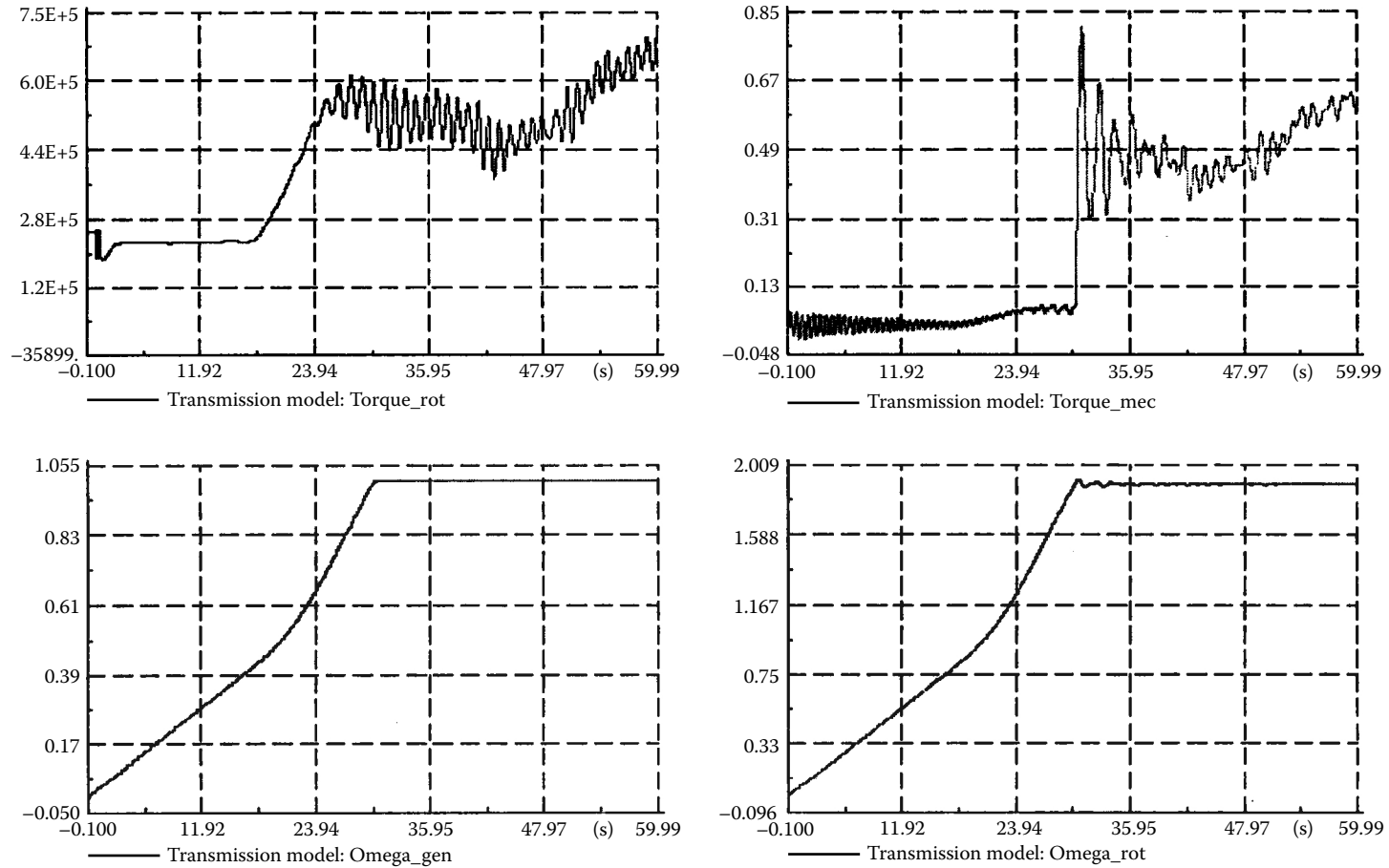


FIGURE 4.33 Transmission model response during start-up.

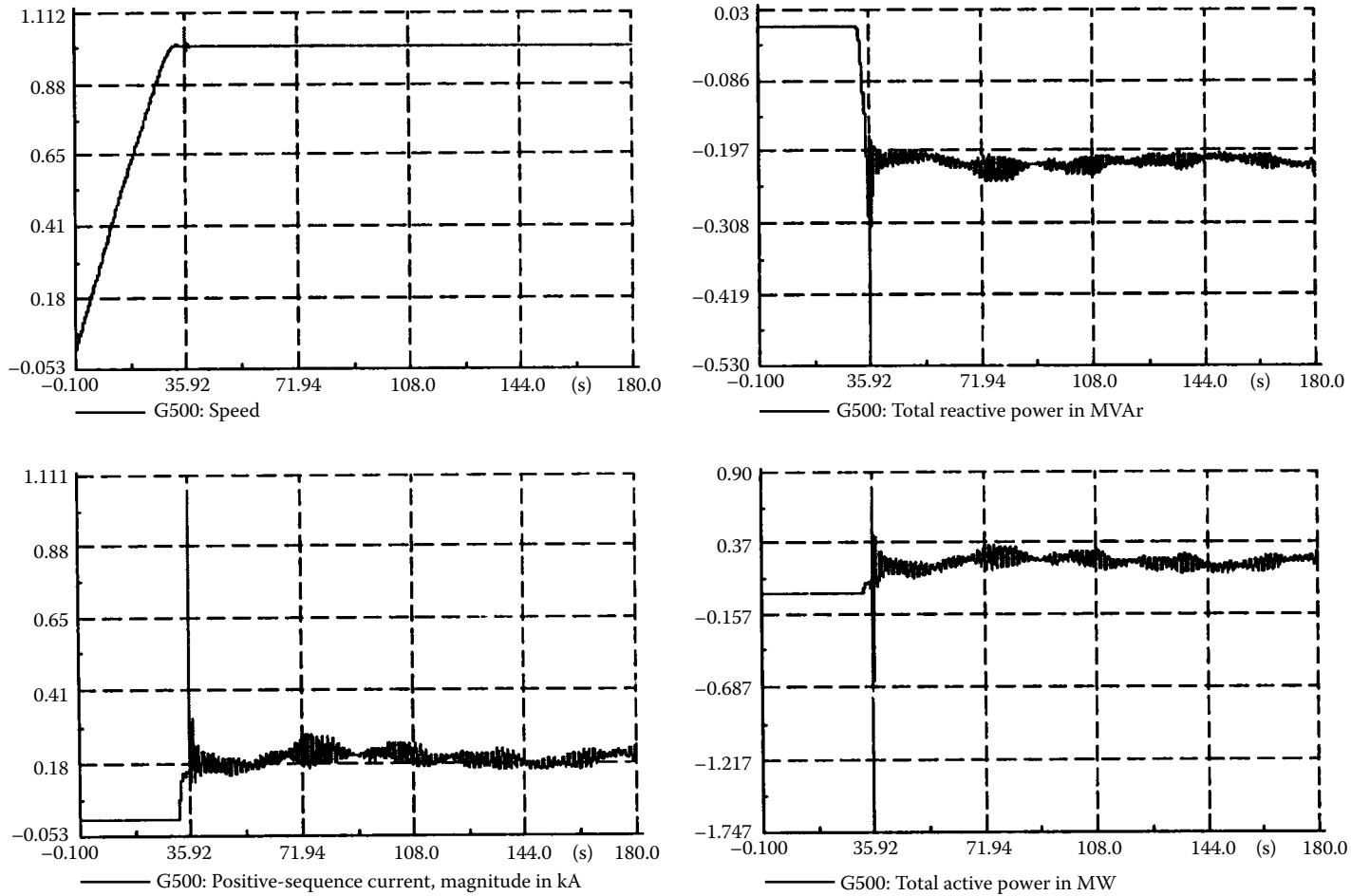


FIGURE 4.34 Direct start-up of a four-pole, 50 Hz, 0.5 MW induction generator (IG).

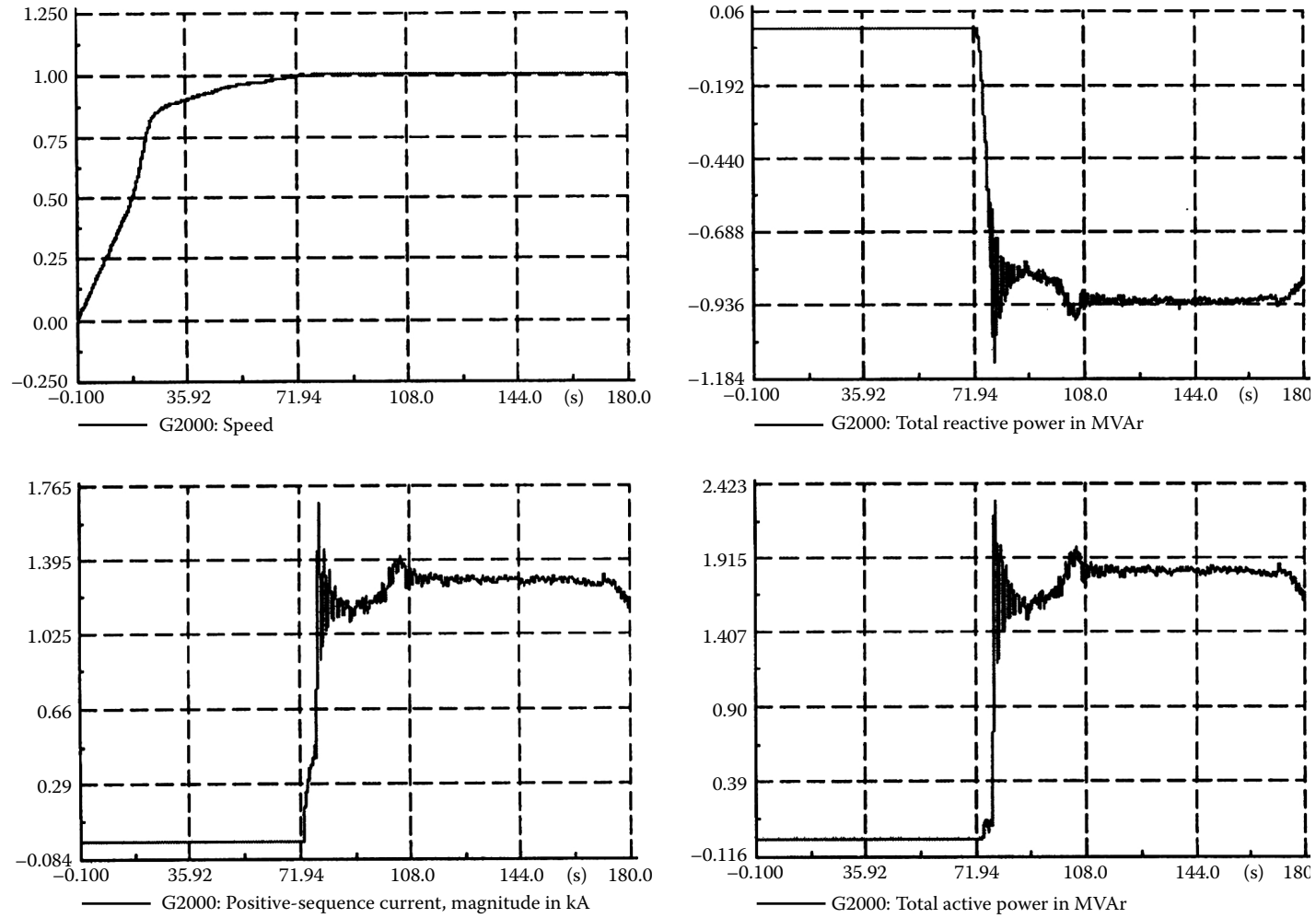


FIGURE 4.35 Start-up and connection via soft-starter to grid at 1500 rpm (2 MVA self-excited induction generator (SEIG)).

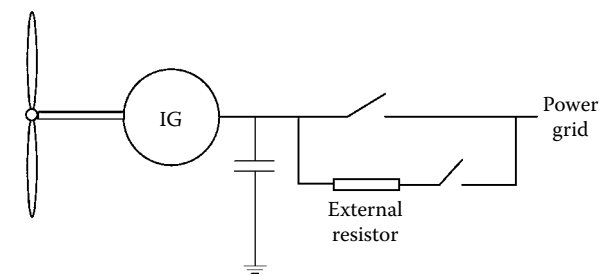


FIGURE 4.36 Connection of induction generators (IGs) with external resistor.

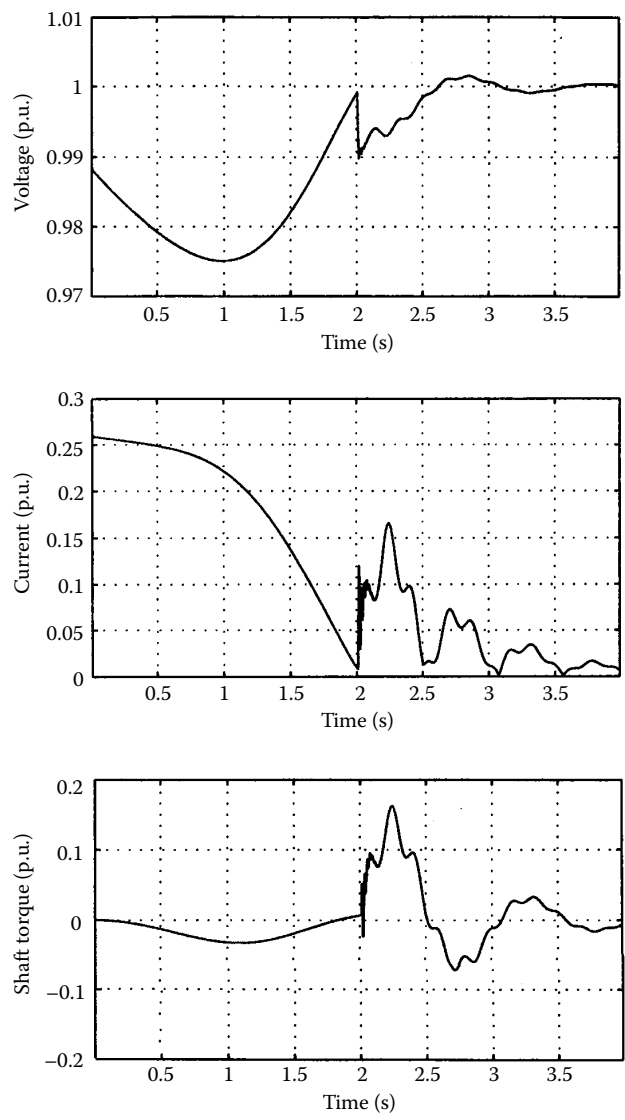


FIGURE 4.37 Voltage, current, and shaft torque vs. time for resistor connection to grid of a 15 kW, 0.8% slip induction generator (IG) with active-stall wind turbine regulation, at no load.

4.14 More on Power Grid Disturbance Transients in Cage Rotor Induction Generators

IGs connected to the power grid are driven by wind turbines, hydroturbines, diesel engines, and so forth. In most cases, the speed of the IG is larger than the speed of the prime mover; thus, a gearbox transmission is required.

Further on, the prime mover has a number of lumped inertias, elastically coupled to each other. The three blades of a standard wind turbine have their inertias as follows: H_{B1} , H_{B2} , and H_{B3} (Figure 4.38). The hub, the gearbox, and the IG rotor have the inertias H_H , H_{GB} , and H_G . Axes and brakes are integrated with them. Spring stiffness and damping elements are also introduced, while the inputs to the wind turbine model are the aerodynamic torques of the blades T_{B1} , T_{B2} , and T_{B3} and the generator torque T_G (Figure 4.38).

The state-space equations of such a drive train in P.U. are given here for convenience:

$$\frac{d}{dt} \begin{bmatrix} [\theta] \\ [\omega] \end{bmatrix} = \begin{bmatrix} [0] & [I] \\ -[2H]^{-1}[C] & -[2H]^{-1}[D] \end{bmatrix} \begin{bmatrix} [\theta] \\ [\omega] \end{bmatrix} + \begin{bmatrix} [0] \\ [2H]^{-1} \end{bmatrix} [T] \quad (4.98)$$

where

$[\theta]$, $[\omega]$, $[T]$ are 6×1 matrix vectors of positions, angular velocities, and torques

$[0]$ and $[1]$ are 6×6 zero and identity matrices

$[H]$ is the 6×6 matrix of inertias

$[C]$ and $[D]$ are stiffness and damping matrices

$$[C] = \begin{bmatrix} C_{HB} & 0 & 0 & -C_{HB} & 0 & 0 \\ 0 & C_{HB} & 0 & -C_{HB} & 0 & 0 \\ 0 & 0 & -C_{HB} & -C_{HB} & 0 & 0 \\ -C_{HB} & -C_{HB} & -C_{HB} & -C_{HGB} + 3H_B & -C_{HGB} & 0 \\ 0 & 0 & 0 & -C_{HGB} & C_{HGB} + C_{GBG} & -C_{GBG} \\ 0 & 0 & 0 & 0 & -C_{GBG} & C_{GBG} \end{bmatrix} \quad (4.99)$$

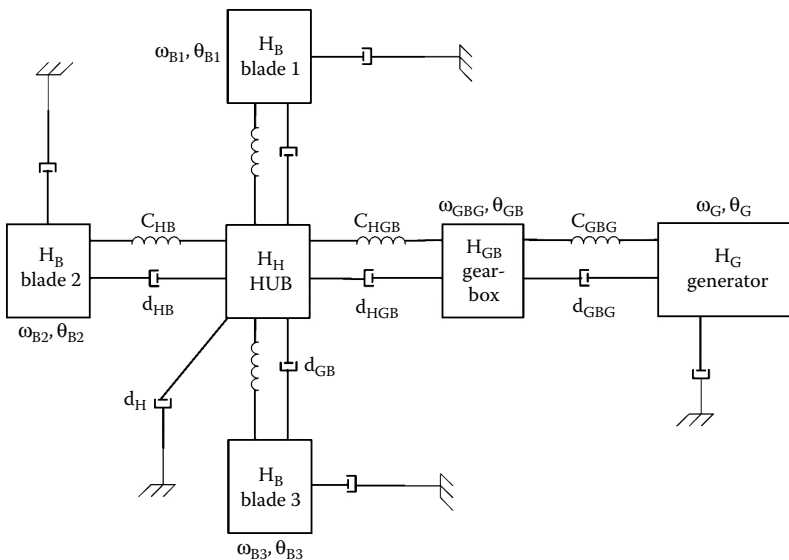


FIGURE 4.38 Wind turbine induction generator (IG) drive train with six inertias.

$$[D] = \begin{bmatrix} D_B + d_{HB} & 0 & 0 & -d_{HB} & & \\ 0 & D_B + d_{HB} & 0 & -d_{HB} & & \\ 0 & 0 & D_B + d_{HB} & -d_{HB} & & \\ -d_{HB} & -d_{HB} & -d_{HB} & D_H + dH_{GB} + 3d_{HGB} & -d_{HGB} & 0 \\ 0 & 0 & 0 & -d_{HGB} & (D_{GB} + d_{HGB} + d_{GBG}) & -d_{GBG} \\ 0 & 0 & 0 & 0 & -d_{GBG} & D_G + d_{GBG} \end{bmatrix} \quad (4.100)$$

The IG model for transients is the already described space-phasor model. However, as during some operation modes the IG may end up as self-excited, supplying its own load after disconnection from the power grid, the model should include the magnetic saturation. The model in Equation 4.89 and Equation 4.90 may be decomposed along d and q axes with Ψ_{1d} , Ψ_{1q} , Ψ_{md} and Ψ_{mq} as variables:

$$\begin{aligned} s\Psi_{1d} &= R_1 I_{1d} + \omega_b \Psi_{1q} + V_d = F_{1d} \\ s\Psi_{1q} &= R_1 I_{1q} - \omega_b \Psi_{1d} + V_q = F_{1q} \\ A_{dd} s\Psi_{md} + A_{dq} s\Psi_{mq} &= -R_2 I_{2d} + (\omega_b - \omega_r) \Psi_{2q} + \frac{X_{2l}}{X_{1l}} F_{1d} \\ A_{dq} s\Psi_{md} + A_{qq} s\Psi_{mq} &= -R_2 I_{2q} - (\omega_b - \omega_r) \Psi_{2d} + \frac{X_{2l}}{X_{1l}} F_{1q} \\ A_{dd,qq} &= X_{2l} \left(\frac{1}{X_{1l}} + \frac{1}{X_{2l}} + \frac{1}{X_m} \right) - X_{2l} \left(\frac{1}{X_m} - \frac{1}{X'_m} \right) \frac{\Psi_{md,q}^2}{\Psi_m^2} \\ A_{dq,qd} &= X_{2l} \left(\frac{1}{X_m} - \frac{1}{X'_m} \right) \frac{\Psi_{md} \Psi_{mq}}{\Psi_m^2} \end{aligned} \quad (4.101)$$

$$\begin{aligned} \omega_1 L_m &= X_m = \omega_1 \frac{\Psi_m(I_m)}{I_m}; \\ \omega_1 L'_m &= X'_m = \omega_1 \frac{d\Psi_m(I_m)}{dI_m} \end{aligned} \quad (4.102)$$

$$I_m = \sqrt{(I_{1d} + I_{2d})^2 + (I_{1q} + I_{2q})^2} \quad (4.103)$$

The rotor flux linkages Ψ_{2d} and Ψ_{2q} and the stator and rotor currents are all dummy variables to be eliminated via the flux/current relationships:

$$\begin{aligned} \Psi_{1d} &= -L_1 I_{1d} + L_m I_{2d} \\ L_1 &= L_{1l} + L_m \\ \Psi_{1q} &= -L_1 I_{1q} + L_m I_{2q} \\ \Psi_{md} &= L_m (-I_{1d} + I_{2d}) \\ \Psi_{mq} &= L_m (-I_{1q} + I_{2q}) \\ \Psi_{2d} &= -L_m I_{1d} + L_2 I_{2d} \\ L_2 &= L_{2l} + L_m \\ \Psi_{2q} &= -L_m I_{1q} + L_2 I_{2q} \end{aligned} \quad (4.104)$$

There are four currents, I_{1d} , I_{1q} , I_{2d} and I_{2q} , and the rotor fluxes Ψ_{2d} and Ψ_{2q} to eliminate from the six expressions of Equation 4.104. Implicitly, the so-called cross-coupling magnetic saturation is accounted for in the above equations [33, 34]. Note that the stator equations are written for the generator mode association of current signs.

The electromagnetic torque T_e is as follows:

$$T_e = \frac{3}{2} p_1 (\Psi_{1d} I_{1d} - \Psi_{1q} I_{1q}) \tag{4.105}$$

The power network is, in general, represented by its sequence equivalents.

Among most abnormal operation modes, we consider here the following:

- Three-phase sudden short-circuits
- Line-to-line short-circuit
- Breaker reclosing before generator defluxing
- One-phase interruption
- Unbalanced system voltages

A three-phase fault at the low voltage side of the transformer, on a 500 kW IG with a 200 kVA parallel capacitor, connected to a local grid containing an 800 kVA (20/0.69 kV) transformer, a 2 km line, and a circuit breaker at the point of common connection is illustrated in Figure 4.39a through Figure 4.39c [32].

About 3 P.U. peak torque at the IG shaft occurs. The propagation of torque through the drive train shows “high fidelity” on the high-speed side, with a more compliant response on the low-speed side

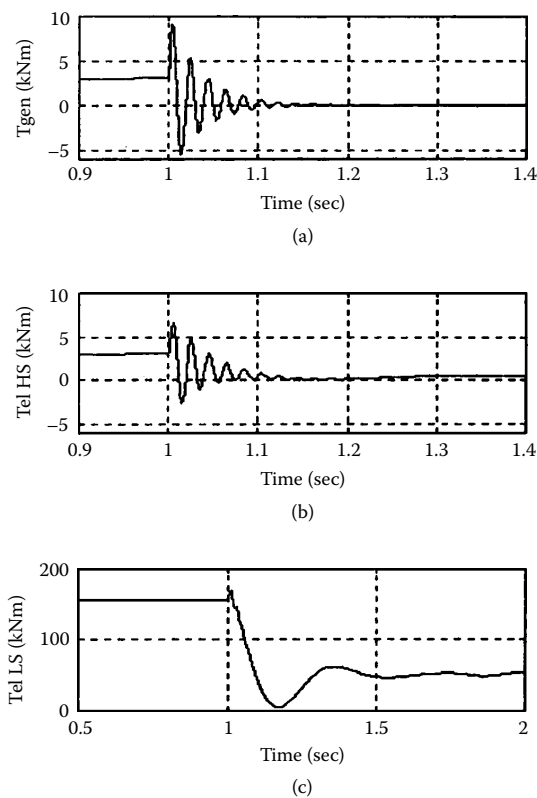


FIGURE 4.39 Three-phase short-circuit at the low voltage busbars: (a) induction generator (IG) torque, (b) high-speed side torque, and (c) low-speed side elasticity torque.

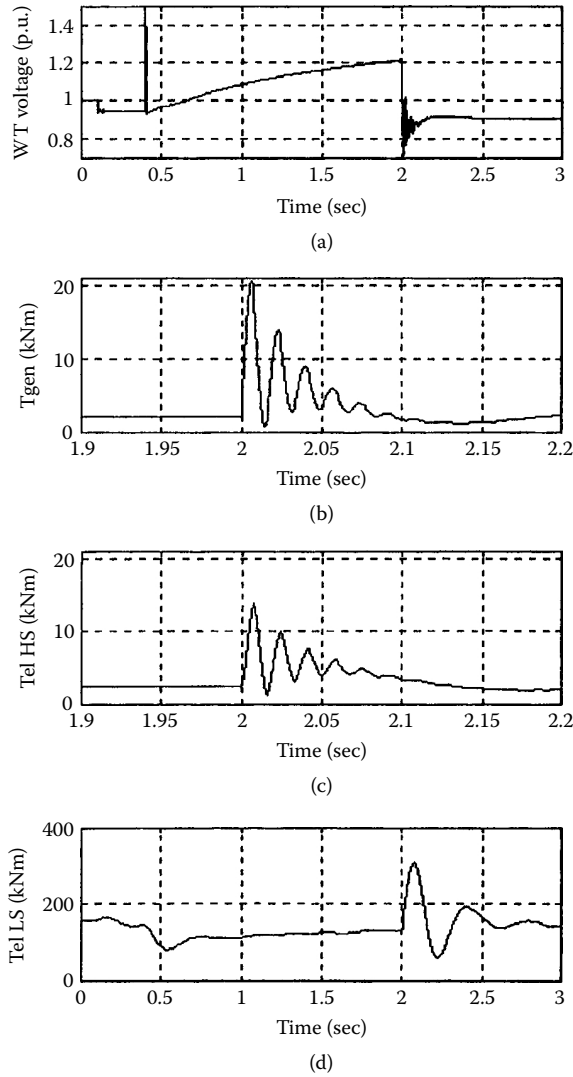


FIGURE 4.40 Breaker reclosing after a remote fault: (a) induction generator (IG) voltage, (b) IG torque, (c) high-speed side torque, and (d) low-speed elasticity torque.

(with a 2 to 3 Hz natural frequency and low damping). The response to a line-to-line fault is similar, but with sustained 100 Hz ($2f_1$) oscillations, as expected. Breaker reclosing, however, produces notably larger torque transients (Figure 4.40a through Figure 4.40d) [32]. A remote fault at 0.1 sec is cleared at 0.4 sec and is followed by a reclosing at 2.0 sec.

The voltage builds up to 120% as the IG stator circuits are open and the 200 kVA capacitors remain at IG terminals. The speed (not shown) does the same. The peak IG torque transients reach 7 P.U. values after reclosing. The gearbox “feels” about 4 P.U. torque oscillations. On the low-speed side, the effect is small. The generator and gearbox stresses are considered potentially harmful. Unbalanced voltages in the local power network produce 100 Hz pulsations in torque. These pulsations may have a notable effect on the fatigue life of the gearbox.

We may conclude here that the “constant speed” IG is vulnerable to power grid disturbances due to its “rigid” response in contrast to variable speed IGs. Note that single-phase SEIG induction transients are to be treated again through the d - q model but in stator coordinates (Reference [1], Chapter 26).

4.15 Summary

- Induction machines with cage rotor and capacitor excitation are coded as SEIGs.
- SEIGs operate typically alone or in a group, autonomously on their particular loads.
- Cage rotor IGs may be connected to the power grid also, with capacitor banks connected at terminals to make up for the reactive power required for their magnetization and to contribute to voltage stabilization.
- SEIGs with capacitor excitation, self-excitation at no load at a frequency f (P.U.) and voltage V_0 (P.U.) are dependent on speed U (P.U.), capacitance C_p at terminals, and on IG parameters. At no load, the slip $S_0 = f_0 - U$ is negative but very small.
- When the SEIG, already self-excited at no load, is loaded, the terminal voltage and frequency vary with load and its power factor. In general, for constant speed and R or R,L load, the load voltage decreases markedly with load. The slip is negative and increases with load.
- For capacitor self-excitation on no load, there should be an initial level of magnetization in the rotor, left from the previous operation, and operation at a notable degree of magnetic saturation.
- The computation of frequency and voltage, for given speed, parallel capacitance C_p , load, and IG parameters, may be approached through two main categories of methods: impedance and admittance types.
- Only the admittance methods, for given frequency, magnetization curve, IG and load parameters, and capacitance, may allow for the computation of slip S (and speed $U = f - S$, $S < 0$) from a second-order algebraic equation. Then, iteratively, the frequency f is changed until the final speed reaches the desired value. Only a few iterations are required. The computation of the corresponding magnetization reactance X_m is straightforward. Then, the airgap emf is found from the magnetization curve ($X_m = f(E_1)$). Further on, the terminal voltage, load current, capacitor current, load power, and so forth, are calculated without any iteration. For successful self-excitation, the solutions of slip S have to be real numbers, and $X_m < X_{max}$. X_{max} is the unsaturated value of X_m .
- The SEIG exhibits a voltage collapse point on its $V(I)$ curve. To extend the stable (linear) part of the $V(I)$ curve, a series capacitance C_s is added. The short-shunt connection performs better. The optimum ratio $K = X_{cs}/C_{cp} = 0.4$ to 0.5 .
- Performance/parameter sensitivity studies reveal that the smaller the IG leakage reactances X_{l1} and X_{l2} in P.U., the better. Also, prime movers with controlled speed are capable of producing notably more power. As the speed goes up with the electric load power, so does the frequency.
- Combined parallel capacitance C_p and speed control are recommended to keep the voltage regulation within 4 to 5% up to full load, with small frequency variations a bonus.
- In applications such as wind machines, where the power decreases with cubic speed, variable speed is desirable when the wind speed decreases notably. Pole-changing SEIGs may handle such situations at low costs. The pole count ratio p_1/p'_1 should vary, generally between one half and two thirds. Two separate windings (of different ratings) may be placed in the stator slots and switched on or off at a certain power (speed) level, or a pole-changing winding may be used for the scope.
- Pole-changing windings with 4/6 pole count ratio, for example, need different connections to provide the same voltage, with the same capacitance (at no load) at different speeds. The key issue is to maintain the airgap flux density (magnetic saturation) at about the same level and the winding factors reasonably high. Attention has to be paid to space harmonics, including subharmonics.
- The commutation of pole count has to be made at a speed that is generally below the peak torque situation for the active connection, in order to safeguard stable transients.
- Three-phase SEIGs may perform on unbalanced loads by accident or by necessity. The investigation of such situations for steady state is performed with the symmetrical components method.
- In general, it is found that the efficiency is notably reduced due to negative sequence losses.
- One phase open, with SEIG connected to the power grid, shows a similar reduction in power at higher losses. The derating of an SEIG (IG) is required for long unbalanced operation, in order to meet the rated temperature limit.

- In some situations, single-phase power is required above 2 to 3 kW, and two-phase induction machines are not available off the shelf.
- Three-phase SEIG connections for single-phase output were proposed. The Steinmetz connection (single-capacitance C^+ in parallel with the second phase, for Δ connection) augmented with series capacitance C_s ($K = X_{cs}/C_{cp} = 0.3 - 0.6$) was demonstrated to extend the $V(I)$ linear curve up to 2.0 P.U. power at reasonable efficiency. The symmetrization of phases is obtained above rated power at a certain value, but the highest phase voltage does not go above 1.2 P.U.
- For powers below 2 to 3 kW, two-phase induction machines are available off the shelf. They were, thus, proposed for small-power single-phase output. A practical solution contains an excitation capacitor C_e to close the auxiliary winding and a series capacitor C_s in the main (power) winding. Again, the method of symmetrical components is to be used to assess the steady-state performance with magnetic saturation consideration as a must. Due to the complexity of the two self-excitation equations, an optimization method seems practical to use to calculate f , C_p , and C_s simultaneously. The Hooke–Jeeves method was proven to be proficient for this endeavor. Again, the series capacitor C_s extends the output power range notably with reasonable voltage self-regulation. Small-power generator sets may take advantage of this inexpensive solution.
- Three-phase SEIG transients occur at self-excitation at no load, load connection and rejection, speed variation, and so forth. The d – q model is used to handle the operation modes that are crucial for power quality and protection of the system design. Again, magnetic saturation has to be included in the model, which may be used first in the space-phaser form.
- Among the main results that we mention after investigating SEIG transients, is that the sudden short-circuit at SEIG terminals leads to 5 P.U. current transients for around 20 msec before the voltage collapses. Also, a safe starting of an IM connected to an SEIG requires only 160% overrating of the SEIG. However, to maintain stable IM operation for 100% step mechanical load, a 300 (400)% overrating is needed.
- Load rejection leads to a slow increase in terminal voltage to its steady-state no-load value. This might be harmful if the speed of the prime mover is not regulated, and speed increases notably after load rejection.
- The parallel connection of SEIGs is required, as there are limitations on the prime-mover power (unit) due to local energy resource limitations. In general, a single variable capacitor is used to self-excite such a group. Again, voltage regulation is better if the speed of some IGs of the group is also regulated with load.
- IGs are connected to the power grid experience connecting transients. Recent international standards drastically limit the voltage change factor, the current change factor, and the voltage flick factor for such transients, in order to maintain power quality in the power grid.
- Direct connection of a cage rotor IG to the grid shows very large transients. However, soft-starter connection leads to much lower transients and is recommended for use, especially for larger power per unit. Alternatively, series resistors may be used for the scope at lower costs but with lower flexibility.
- Power grid disturbances (short-circuit, breaker reclosing, one phase open, etc.) may produce very high-peak torques in the generator and in the gearbox (if any), 7 P.U. and 3.0 P.U. oscillations, respectively, for breaker reclosing after clearing a distant short-circuit. These torque oscillations may reduce the fatigue life of the IG shaft and of the gearbox. The transmission power train is to be modeled as a multiple inertia system with stiffness and damping connection elements.
- Electrical flicker is a measure of the voltage variation that may cause eye disturbance for the consumer. The variation of wind power (speed) in time may induce flicker during continuous operation. Flicker may also be induced during switchings. For constant speed IGs, this is a particularly sensitive issue [35, 36].

References

1. I. Boldea, and S.A. Nasar, *Induction Machine Handbook*, CRC Press, Boca Raton, FL, 2001.
2. E.D. Basset, and F.M. Potter, Capacitive excitation of induction generators, *Electrical Eng.*, 54, 1935, pp. 540–545.
3. S.S. Murthy, O.P. Malik, and A.K. Tandon, Analysis of self-excited induction generators, *Proc. IEE*, 129, Part. C, 7, 1982, pp. 260–265.
4. L. Ouazone, and G. McPherson, Analysis of the isolated induction generator, *IEEE Trans.*, IAS-102, 8, 1983, pp. 2793–2798.
5. L. Shridher, B. Singh, and C.S. Tha, Towards improvements in the characteristics of selfexcited induction generators, *IEEE Trans.*, EC-8, 1, 1993, pp. 40–46.
6. S.P. Singh, B. Singh, and M.P. Jain, A new technique for the analysis of selfexcited induction generator, *EMPS J.*, 23, 6, 1995, pp. 647–656.
7. T.F. Chan, and L.L. Lai, Steady state analysis and performance of a stand alone three phase induction generator with asymmetrical connected load impedances and excitation capacitances, *IEEE Trans.*, EC-16, 4, 2001, pp. 327–333.
8. N. Ammasaigounden, M. Subbiah, and M.R. Krishnamurthy, Wind driven self-excited pole changing induction generator, *Proc. IEE*, 133B, 6, 1986, pp. 315–321.
9. T.F. Chan, Analysis of self-excited induction generators using an iterative method, *IEEE Trans.*, EC-10, 3, 1995, pp. 502–507.
10. K.S. Sandhu, and S.K. Jain, Operational aspects of self-excited induction generator using a new model, *EMPS J.*, 27, 2, 1999, pp. 169–180.
11. S. Rajakaruna, and R. Bonert, A technique for the steady state analysis of a selfexcited induction generator with variable speed, *IEEE Trans.*, EC-8, 4, 1993, pp. 757–761.
12. L. Shridha, B. Singh, C.S. Tha, B.P. Singh, and S.S. Murthy, Selection of capacitors for the selfregulated short shunt self-excited induction generators, *IEEE Trans.*, EC-10, 1, 1995, pp. 10–16.
13. E. Suarez, and G. Bortolotto, Voltage-frequency control of a self-excited induction generator, *IEEE Trans.*, EC-14, 3, 1999, pp. 394–401.
14. P. Chidambaram, K. Achutha, M. Subbiah, and M.R. Krishnamurthy, A new pole changing winding using star/star delta switching, *Proc. IEE*, B-EPA-130, 2, 1983, pp. 130–136.
15. R. Parimelalasan, M. Subbiah, and M.R. Krishnamurthy, Design of dual speed single-winding induction motors — a unified approach, Record IEEE-IAS-1976 Annual Meeting, paper 398, pp. 1071–1079.
16. N. Ammasaigounden, M. Subbiah, and M.R. Krishnamurthy, Wind-driven selfexcited pole-changing induction generators, *Proc. IEE*, 133 part B, 5, 1986, pp. 315–322.
17. A.M. Bahrani, Analysis of selfexcited induction generators under unbalanced conditions, *EMPS J.*, 24, 2, 1996, pp. 117–129.
18. A.W. Ghorashi, S.S. Murthy, B.P. Singh, and B. Singh, Analysis of winddriven grid connected induction generators under unbalanced conditions, *IEEE Trans.*, EC-9, 2, 1994, pp. 217–223.
19. T.F. Chan, and L.L. Lai, A novel single-phase self-regulated self-excited induction generator using three phase machine, *IEEE Trans.*, EC-16, 2, 2001, pp. 204–208.
20. T.F. Chan, and L.L. Lai, Single-phase operation of a three-phase induction generator with Smith connection, *IEEE Trans.*, EC-17, 1, 2002, pp. 47–54.
21. T. Fukami, Y. Kaburaki, S. Kawahara, and T. Miyamoto, Performance analysis of self-regulated and self-excited single phase induction machine using a three phase machine, *IEEE Trans.*, EC-14, 3, 1999, pp. 622–627.
22. Y.H.A. Rahim, I.I. Alolah, and R.I. Al-Mudaiheem, Performance of single phase induction generators, *IEEE Trans.*, EC-8, 3, 1993, pp. 389–395.
23. M.H. Salama, and P.G. Holmes, Transients and steady-state load performance of stand-alone self-excited induction generator, *Proc. IEE*, EPA-143, 1, 1996, pp. 50–58.

24. O. Ojo, Performance of self-excited single-phase induction generators with shunt, short-shunt and long-shunt excitation connections, *IEEE Trans.*, EC-14, 1, 1999, pp. 93–100.
25. L. Wang, and J.Y. Su, Dynamic performace of an isolated self-excited induction generator under various loading conditions, *IEEE Trans.*, EC-14, 1, 1999, pp. 93–100.
26. B. Singh, L. Shridar, and C.B. Iha, Transient analysis of selfexcited generator supplying dynamic load, *EMPS J.*, 27, 9, 1999, pp. 941–954.
27. A.H. Al-Bahrani, and N.H. Malik, Voltage control of parallel operated self-excited induction generators, *IEEE Trans.*, EC-8, 2, 1993, pp. 236–242.
28. C.H. Lee, and L. Wang, A novel analysis of parallel operated self-excited induction generators, *IEEE Trans.*, EC-14, 2, 1998, pp. 117–123.
29. L. Mihet-Popa, F. Blaabjerg, and I. Boldea, Wind turbine generator modeling and simulation where rotational speed is the controlled variable, *IEEE Trans.*, IA-40, 1, 2004, pp. 8–13.
30. T. Thiringer, Grid friendly connected of constant speed wind turbines using external resistors, *IEEE Trans.*, EC-17, 4, 2002, pp. 537–542.
31. A. Larsson, Guidelines for grid connection of wind turbines, Record of 15th International Conference on Electricity Distribution, Nice, France, June 1–4, 1999.
32. S.A. Papathanassiou, and M.P. Papadopoulos, Mechanical stresses in fixed speed wind turbines due to network disturbances, *IEEE Trans.*, EC-16, 4, 2001, pp. 361–367.
33. P. Vas, K.E. Hallenius, and J.E. Brown, Cross-saturation in smooth airgap electrical machines, *IEEE Trans.*, EC-1, 1, 1986, pp. 103–112.
34. I. Boldea, and S.A. Nasar, Unified treatment of core loss and saturation in the DQ models of electrical machines, *Proc. IEE*, 134B, 6, 1987, pp. 355–363.
35. A. Larsson, Flicker emission of wind turbines during continuous operation, *IEEE Trans.*, EC-17, 1, 2002, pp. 114–118.
36. A. Larsson, Flicker emission of wind turbines caused by switching operations, *IEEE Trans.*, EC-17, 1, 2002, pp. 119–123.